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March 1984

INDUSTRIAL HARDENING AND POPULATION BLAST SHELTER TESTS AT THE DIRECT COURSE EVENT

FINAL REPORT

for

FEDERAL EMERGENCY MANAGEMENT AGENCY
WASHINGTON, D.C. 20472

Contract No. EMW-C-1097
Work Unit 1121E

SCIENTIFIC SERVICE, INC.

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This report presents the results of experiments conducted for the Federal Emergency Managment Agency at the DIRECT COURSE high explosive test on 26 October 1983 at White Sands Missile Range. The DNA-sponsored DIRECT COURSE event consisted of the detonation of 609 tons of ANFO at a height of burst of 166 ft. The experiments discussed in this report were conducted in support of Civil Defense planning and involved industrial protection and shelter design criteria. One group of

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experiments was designed to gather further experimental data on the concept of clustering as a method for hardening of industrial equipment. Two one-fifth scale model buildings were tested to obtain information on frame response, building collapse, and survivability of upgraded basements. Model basements walls and model shelters were also tested, and six types of expedient closures were fielded to test closure materials that could be easily installed by hand.

(DETACHABLE SUMMARY)

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by

C. Wilton and J.V. Zaccor

for

Federal Emergency Management Agency
Washington, D.C. 20472

Contract No. EMW-C-1097, Work Unit 1121 E

FEMA REVIEW NOTICE:

This report has been reviewed in the Federal Emergency Management Agency and approved for publication. Approval does not signify that the contents necessarily reflect the views and policies of the Federal Emergency Management Agency.

Scientific Service, Inc.
517 East Bayshore, Redwood City, CA 94063

(DETACHABLE SUMMARY)

INDUSTRIAL HARDENING AND POPULATION BLAST SHELTER TESTS AT THE DIRECT COURSE EVENT

This report presents the results of FEMA-sponsored SSI experiments conducted at the DIRECT COURSE high explosive test on October 26, 1983 at White Sands Missile Range, New Mexico. This test was conducted by DNA and consisted of the detonation of 609 tons of ANFO at a height of burst of 166 ft.

Scientific Service, Inc., under the sponsorship of FEMA, designed and conducted experiments at DIRECT COURSE in the areas of industrial protection, shelter design criteria, and model basement walls, closures, and model shelter experiments. The following is a brief description of the results and a summary of the conclusions for these experiments.

Industrial Protection Experiments

The primary objective of this group of experiments was to gather further experimental data to verify the concept of clustering as a method for the hardening of industrial equipment. In this technique the equipment to be protected is clustered together in an open area, and all items are secured together by means of strapping, banding, etc., with shock-absorbing materials placed between and around the items. The specific objectives were to verify the concept by: (1) Testing of clusters of actual equipment under conditions similar to that for clusters of simulated equipment conducted at the MILL RACE event; (2) Testing of an actual equipment cluster inside a structure where it would be exposed to flying wall fragments; and (3) Testing of simulated equipment clusters (55-gallon drums) under a wider range of conditions than were investigated at the MILL RACE event including higher overpressures, larger clusters, and a wider range of tie materials. Secondary objectives were to further study the behavior of unhardened industrial equipment under blast loading to determine its vulnerability and to conduct some preliminary tests on hardening methods for electronic equipment.

Two actual equipment clusters, consisting of nine band saws, were tested in the open at approximately 20 psi, one on a concrete pad and one on a dirt pad. In both cases, although the sheet metal legs were damaged beyond reasonable repair, all but one of the pieces of equipment were in good condition and could be rapidly repaired. An additional cluster was tested inside a building and exposed to fragments. In this case, the cluster displaced to a point where one of the main beams of the collapsing building impacted on the cluster, and only three items of equipment survived.

The results from the simulated equipment clusters, 55-gallon drums filled with water, were as follows:

At the expected 40 psi range (actual pressures 20% to 30% higher) considerable damage occurred; the resulting conclusion was that clustering at this pressure level would not be a practical technique for hazardous materials in drums. This method, applied to rigid equipment with stronger banding techniques, however, might make clustering work at this level.

At the expected 30 psi level (actual pressures somewhat higher) there was also considerable damage due to the drums losing their lids and deforming so that the webbing holding the clusters together loosened and released additional drums from the cluster. It was concluded from the results of this experiment that, at this overpressure range, rigid body items could be successfully clustered if bound with at least the 8,000-pound webbing used; fluid filled drums would also be successfully clustered at this pressure level providing the drums maintained their integrity and remained sealed.

At the expected 20 psi range a variety of binding materials were investigated. It was concluded that a minimum of a 4,000 pound tensile strength binding material was required and that clustering was a valid concept for hazardous materials in drums at this pressure level. It would still be necessary, however, that the lids stay on and the drums retain their integrity.

The tests of the unhardened equipment essentially confirmed the need for using hardening techniques such as the clustering concept. With regard to the electronic equipment tests, a technique of immersing delicate equipment in alcohol proved successful, which suggests that extremely valuable, delicate electronic equipment can be easily hardened to 20 psi.

Basic Shelter Design Criteria Experiments

Two one-fifth scale model buildings, one concrete and the other steel, were tested at the expected 50 psi range (actual overpressure approximately 70 psi). The objective of this test was to obtain information on frame response, building collapse, and survivability of upgraded basements.

The test was successful in that valuable data were obtained on mode of failure and debris translation. Very little data were obtained on frame response, because of problems with the cameras, or on survivability of the upgraded basements, because of the higher than planned overpressures. One of the most important results of this test was the conclusion that valuable information can be gained from structural models of this size in these high explosive events.

Model Basement Wall Experiments

Eight model basements, each containing three test walls, were tested, six at the expected 50 psi level (actual overpressure approximately 80 psi) and two at the expected 18 psi range (estimated actual overpressure 23 psi). The objectives of this experiment were to test the effects of various types of backfill, to gather statistical data on basement wall collapse and to determine the effect on the loading of the basement walls of the blast wave's reflecting off an aboveground structure.

Because of the higher than planned overpressures, all the walls failed and very little information was gained on the effect of the various types of backfill, and no statistical data were obtained. Significant data were obtained on the effect of the aboveground structure, however, indicating that even though an aboveground structure does not survive very long, the reflected blast wave off this structure has a significant effect on the overpressure loading on the basement walls.

Closure Tests

This experiment involved the testing of six types of expedient closures consisting of wood, sheet steel, and corrugated sheet steel at the expected 50 psi range (actual estimated overpressure 65 psi). The objective was to test lightweight closure materials, i.e., materials that could be easily installed by hand.

Of the six closures tested, three survived. These were the good wood, the poor wood, and the corrugated sheet steel. The three sheet steel closures failed, but it was concluded that in a real shelter situation, where they could be fastened

down and where soil would be spread over the entire area rather than just on the closures, one or more of those that failed would probably have survived.

Model Shelter Tests

Six model shelters were tested, three at the expected 50 psi level (actual estimated overpressure 80 psi) and three at the expected 100 psi level (actual estimated overpressure 118 psi). The objective of this experiment was to test the guidance for the upgrading of basements at the 50 and 100 psi levels.

Because of the higher than expected overpressures all the shelters failed.

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This report describes the experiments conducted by Scientific Service, Inc., for the Federal Emergency Management Agency at the Defense Nuclear Agency's DIRECT COURSE Event, October 26, 1983, at the White Sands Missile Range, New Mexico. The authors wish to take this opportunity to thank those involved in the project.

U.S. Army Corps of Engineers, Waterways Experiment Station provided liaison, instrumentation, and construction inspection. Particular thanks are due to Bill Huff, James Watt, Stan Woodson, and T.C. Jones, whose cooperation and assistance were invaluable to the success of the project. The support of the White Sands Missile Range onsite support staff is gratefully acknowledged.

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Section 1
INTRODUCTION

BACKGROUND

Scientific Service, Inc., under the sponsorship of the Federal Emergency Management Agency (FEMA), is at present conducting four interrelated programs that support crisis relocation planning. These programs include the development and testing of shelter design options for both key worker and host area shelters, the development and testing of an industrial protection manual, the development of casualty predictions for as-built and upgraded basement shelters, and the development and implementation of shelter development plans for host area communities.

The DIRECT COURSE event offered a unique opportunity for FEMA to demonstrate, using both models and full scale test objects, the validity and practicality of a number of shelter upgrading and industrial hardening concepts that will support crisis relocation planning. DIRECT COURSE was a high explosive test conducted on October 26, 1983 at the White Sands Missile Range in New Mexico. The test was sponsored by the Defense Nuclear Agency (DNA) and consisted of the detonation of approximately 609 tons of ammonium nitrate-fuel oil (ANFO) mixture at a height of burst (HOB) of 166 ft.

OBJECTIVES

As part of the programs noted above, Scientific Service, Inc., is producing a number of technical reports and guidance manuals on the subjects of shelter upgrading and industrial protection. The objective of the tests conducted in

DIRECT COURSE and in the previous MILL RACE event was to gather dynamic test data to assist in the development of the manuals and reports. Areas of interest included high rise frame response, closures for shelters, the response of basement walls to blast loading, the performance of industrial equipment and machinery under blast loading, and tests of shelter upgrading guidance.

REPORT ORGANIZATION

Five groups of experiments were conducted: industrial protection experiments (DNA Nos. 4100 through 4130), basic shelter design criteria experiments (DNA Nos. 4140 and 4145), model basement wall experiments (DNA Nos. 4150 and 4160), closure experiments (DNA No. 4170), and model shelter experiments (DNA Nos. 4180 and 4185). A total of 42 experiments were fielded. These are summarized in Table 1-1. SSI also supported six additional experiments for the Oak Ridge National Laboratory (DNA Nos. 4211 through 4223). The descriptions and results of these experiments are reported in an ORNL report.

This report describes all of the SSI experiments in detail, outlining the objectives of each, the design parameters used, the construction methods and materials, the instrumentation, and the test results, observations, and conclusions.

This report is organized as follows:

Section 2 Industrial Protection Experiments
Section 3 Basic Shelter Design Criteria Experiments
Section 4 Model Basement Wall Experiments
Section 5 Closure Experiments
Section 6 Model Shelter Experiments
Section 7 Program Summary

Table 1-1

LIST OF EXPERIMENTS

Industrial Protection Experiments		Expected Peak Overpressure
4100-A	Equipment Cluster (9 band saws) on concrete pad	20 psi
4100-B	Equipment Cluster (9 band saws) on dirt surface	20 psi
4110	Equipment Cluster (9 band saws) inside WES structure	25 psi
4115-A	Simulated Equipment Cluster (7-barrel) on concrete pad	40 psi
4115-B	Simulated Equipment Cluster (7-barrel) on dirt surface	40 psi
4115-C	Simulated Equipment Cluster (19-barrel) on concrete surface	40 psi
4115-D	Simulated Equipment Cluster (19-barrel) on dirt surface	40 psi
4120-A	Simulated Equipment Cluster (10-barrel) on concrete pad	30 psi
4120-B	Simulated Equipment Cluster (14-barrel) on dirt surface	30 psi
4120-C	Simulated Equipment Cluster (14-barrel) on concrete surface	30 psi
4120-D	Simulated Equipment Cluster (10-barrel) on dirt surface	30 psi
4120-E	Simulated Equipment Cluster (7-barrel) on dirt surface	30 psi
4125-A	Simulated Equipment Cluster (7-barrel) on dirt surface*	20 psi
4125-B	Simulated Equipment Cluster (7-barrel) on concrete surface	20 psi
4125-C	Simulated Equipment Cluster (7-barrel) on dirt surface*	20 psi

* Also included electronic equipment test, see discussion Section 2

Table 1-1(contd)

		Expected Peak Overpressure
Industrial Protection Experiments (contd)		
4130-A	Equipment Test (Band Saw, end on)	20 psi
4130-B	Equipment Test (Band Saw, side on)	20 psi
4130-C	Equipment Test (Table Saw)	20 psi
4130-D	Equipment Test (Power Supply)	20 psi
4130-E	Equipment Test (Power Supply)	20 psi
4130-F	Equipment Test (Band Saw, end on)	20 psi
4130-G	Equipment Test (Band Saw, side on)	20 psi
4130-H	Equipment Test (Table Saw)	20 psi
Basic Shelter Design Criteria Tests		
4140	1/5 Scale Model Steel Frame Building	50 psi
4145	1/5 Scale Model Concrete Frame Building	50 psi
Model Basement Wall Tests		
4150-A	Model basement, sand backfill	50 psi
4150-B	Model basement, soil backfill	50 psi
4150-C	Model basement, gravel backfill	50 psi
4150-D	Model basement, gravel backfill, aboveground frangible wall	50 psi
4150-E	Model basement, soil backfill, aboveground frangible wall	50 psi
4150-F	Model basement, sand backfill, aboveground frangible wall	50 psi

Table 1-1(contd)

		Expected Peak Overpressure
Model Basement Wall Tests		
4160-A	Model Basement, soil backfill	18 psi
4160-B	Model Basement, soil backfill, aboveground frangible wall	18 psi
Closure Tests		
4170-A	24-gage Steel closure on 4 ft X 4 ft opening,	50 psi
4170-B	18-gage Steel closure on 4 ft X 4 ft opening,	50 psi
4170-C	13-gage Steel closure on 4 ft X 4 ft opening,	50 psi
4170-D	Wood closure (poor wood) on 4 ft X 6 ft opening,	50 psi
4170-E	Corrugated Steel closure on 4 ft X 6 ft opening,	50 psi
4170-F	Wood closure (good wood) on 4 ft X 6 ft opening,	50 psi
Model Shelter Tests		
4180-A	1/10 scale model shelter, not upgraded	50 psi
4180-B	1/10 scale model shelter, 1/4 span shoring	50 psi
4180-C	1/10 scale model shelter, 1/3 span shoring	50 psi
4185-A	1/10 scale model shelter, not upgraded	100 psi
4185-B	1/10 scale model shelter, 1/3 span shoring	100 psi
4185-C	1/10 scale model shelter, 1/4 span shoring	100 psi

Section 2
INDUSTRIAL PROTECTION EXPERIMENTS
DNA Nos. 4100 through 4130

INTRODUCTION

In support of the continuing FEMA program of industrial protection planning, a series of experiments of equipment hardening were conducted during the 1981 MILL RACE event (Ref. 1). The results from this series of tests combined with analytical work (reported in Ref. 2) indicate that the clustering of equipment is one of the most promising onsite hardening techniques where direct burial is not feasible, and few resources are available for other forms of hardening.

In this technique the equipment to be protected is clustered together in an open area (such as a parking lot), and all items are secured together by means of strapping, banding, or welding, with sandbags, tires, lumber, or other shock-absorbing materials placed between and around the items. Providing that the cluster can be adequately secured as a unit, all elements within it will become less vulnerable than if they were standing alone. Vulnerability is reduced because the cluster presents a lower profile (i.e., ratio of height to depth) to the blast wave and, thus, is less likely to overturn and be damaged by impact or impacts (in the case of tumbling) on the ground surface. The cluster also results in a greater ratio of total weight to area exposed to the blast, so that the cluster will not slide as far, thus reducing the probability of damaging impacts with other objects. Further, the cluster is inherently less vulnerable to missile damage.

OBJECTIVES

The primary objective of this group of experiments was to further verify the clustering concept by:

1. The testing of clusters of actual equipment under conditions similar to that for the clusters of simulated equipment (55-gallon drums) conducted at MILL RACE.

2. Testing of an actual equipment cluster inside a structure where it was exposed to flying wall fragments.

3. Testing of simulated equipment clusters (55-gallon drums) under a wider range of conditions than were investigated at MILL RACE including:

   a. Higher overpressures
   b. Larger clusters
   c. Wider range of tie materials

Secondary objectives were to further study the behavior of unhardened industrial equipment under blast loading to determine its vulnerability and to conduct some preliminary tests on hardening methods for electronic equipment.

DNA Nos. 4100 and 4110 - EQUIPMENT CLUSTERS

Three clusters were tested. Each cluster consisted of nine metal-cutting bandsaws. Cushioning material, consisting of automobile tires, was placed between the saws, and the cluster was tied together with seatbelt webbing. Each cluster was approximately 3½ ft wide with a depth, D, in the direction of the blast of 9 ft. The overall density of the array was about 17 lb/ft^3. This particular cluster arrangement was selected to model, as nearly as possible, the behavior of a heavy equipment cluster exposed to a 1 Mt weapon. The heavy equipment cluster selected to model was one that had been assembled on a trial basis and that had a minimum depth, D = 20 ft, and a density of 50 lbs/ft^3 (Ref. 2). Calculations given in Ref. 2 show that the cluster would not overturn, nor should it slide more than a distance D provided that:

$$D = 1.5(I_q/F)^{2/3} \tag{1}$$

where D = the minimum horizontal depth of the cluster (ft)

I_q = the dynamic pressure impulse (psi-s)

F = the ratio of the density of the cluster to steel

and it is assumed that the height of the cluster is less than D/3.

To illustrate the scaling involved, assume it is desired to model, in a 1 kt test using real equipment, a full scale cluster having a D = 20 ft and an F = 0.1 when exposed to a 1 Mt weapon burst. This means that D and/or F have to be reduced so that the above equation holds for a reduction in I_q of a factor of 10. This could be accomplished, for example, by reducing F by a factor of 10 to a value of 0.01. This, however, is an impractically low value of F, since typical lightweight machine tools have F values of from 0.19 to 0.044.

On the other hand, all the change might be made in the D factor, which would reduce it by almost a factor of 5 down to slightly more than 4 ft. This would make it virtually impossible to meet the required height-to-depth ratio as well as to include most items of real equipment. The cluster used in DIRECT COURSE had a D of 9 ft and an F of 0.034 -- values that avoid the problems discussed above and were convenient to work with. Note that what this type of scaling means is that the model scale case had the same likelihood of overturning as the full scale case and that in both cases the cluster will slide less than the distance D. Likelihood of overturning means that the model scale cluster will be accelerated to the same fraction of the velocity needed for overturning as in the full scale case, which for the clusters used is about 2/3.

Note that the theory indicates the behavior is independent of the dimension of the cluster parallel to the shock front, which we will call the width. In the real case when the direction of the blast wave is unknown, square clusters are optimum. For testing purposes, however, it makes sense to reduce the width since this reduces testing costs. The model scale cluster used had a width of approximately 0.4 D.

4100-A: Equipment Cluster on Concrete Pad

A cluster consisting of nine bandsaws cushioned with tires and banded with seatbelt webbing was placed on a concrete pad at the expected 20 psi range. The

dimensions of this cluster were 9 ft 3 in. by 3 ft 6 in. A photograph of this cluster being constructed is shown in Figure 2-1A. In Figure 2-1B the equipment cluster on the concrete pad is to the right, and the one on the dirt pad (discussed below) is to the left. Also shown in this photograph is the charge. The distance from ground zero to the cluster was 740 ft. A sketch showing the locations of each piece of equipment in the cluster is shown in Figure 2-2.

The estimated overpressure from the BRL northern instrumentation radial, located approximately 55 feet from this experiment was 23.22 psi. Measurements obtained from WES, which were directly in line with this experiment but closer to the charge, indicated that the pressures in this area might have been considerably higher, possibly as much as 20 to 30 percent. Posttest photographs are shown in Figure 2-3 and 2-4.

It had been estimated that this cluster, with a horizontal dynamic pressure impulse of $I_q = 0.3$ psi-s, would translate approximately 3 ft, and not overturn, if the array maintained its integrity.* The displacement observed was 6 ft (corresponding to an $I_q = 0.42$), and the array came apart to the extent that the first row of equipment was lifted over the second row (compare Figure 2-3 with Figure 2-2) when the banding ceased to hold the array together because the light sheet metal portion of the equipment deformed. Posttest examination of the equipment indicated that, although the legs of the bandsaws were damaged beyond repair, many of the saws themselves were still operable. The posttest condition of each of the items is listed below along with the actual repair time to put them into running condition.

Number	Condition	Minutes to Repair
3	?	?
4	Good	0.0
6	Good	4.0
9	Good	14.0
7	Good	7.5

* Overturning should not occur where translation, X, of the array is less than the depth, D; may or may not occur for X near D; and will probably occur for an X that is greater than 110%, or so, of D.

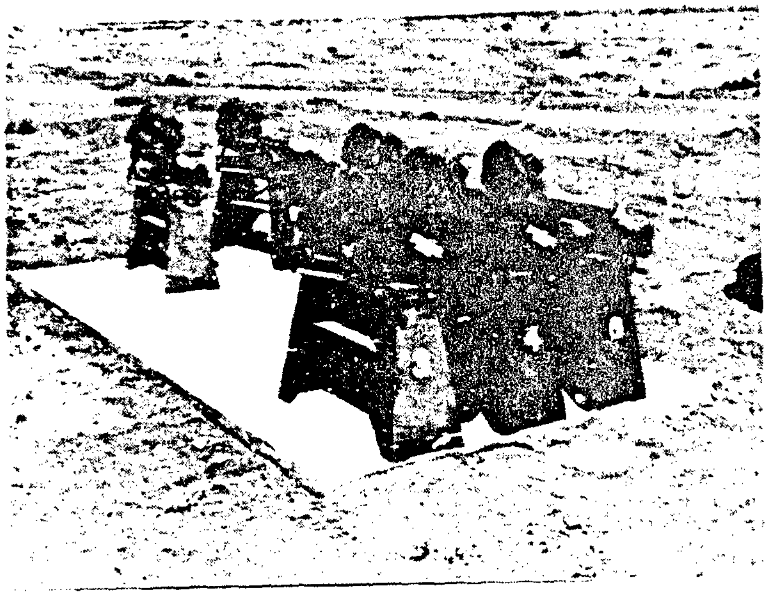
Number	Condition	Minutes to Repair
8	Good	1.0
12	Good	0.0
11	Good	0.0
13	Good	1.0

4100-B: Equipment Cluster on Dirt Pad

This cluster also included nine saws and was 9 ft 3 in. long and 3 ft 4 in. wide. A sketch showing the pretest locations is shown in Figure 2-5 and posttest photographs in Figure 2-6. It was calculated that this cluster would also move approximately 5 ft for the impulse measured on the gauge line nearest this experiment. This is what was observed when account is taken of the displacing of the front row in the array over the top of the remaining two rows. Again, for the array on soil, many of the items of equipment survived well enough to be repaired quickly. The posttest condition of the operating portion of each of the items along with the repair time is presented below.

Number	Condition	Minutes to Repair
1	Good	3.0
2	Scrap	na
5	Good	2.0
15	Good	19.0
18	Good	8.5
19	Good	0.0
16	Good	9.0
17	Good	3.0
14	Good	0.0

A



B

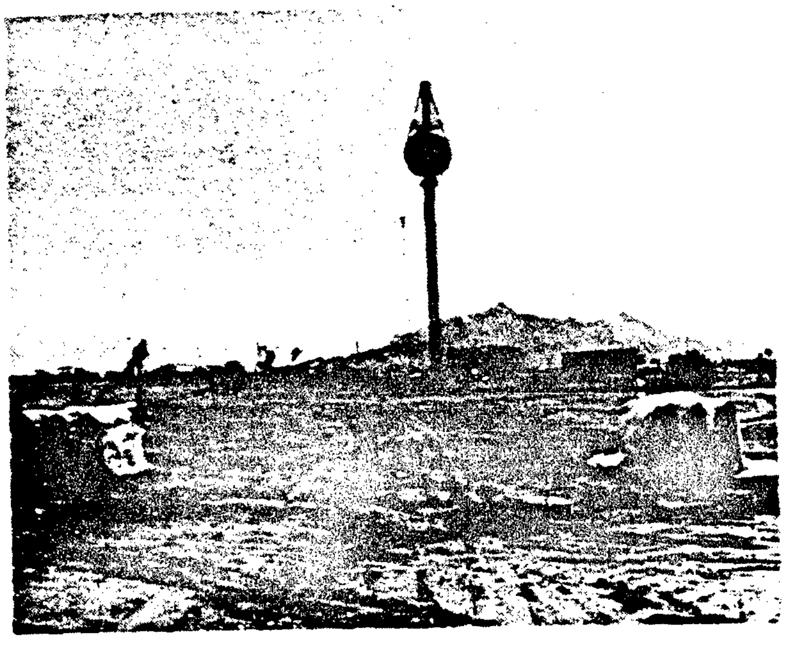


Fig. 2-1. Experiment 4100-A Under Construction.

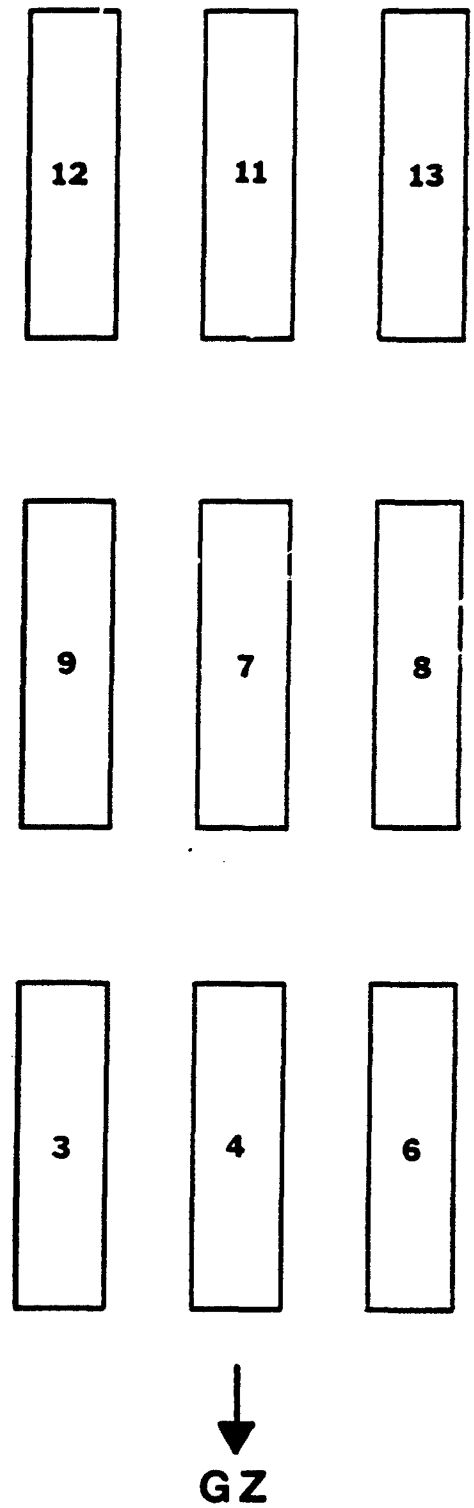


Fig. 2-2. Sketch Showing Location of Each Piece of Equipment in Experiment 4100-A.

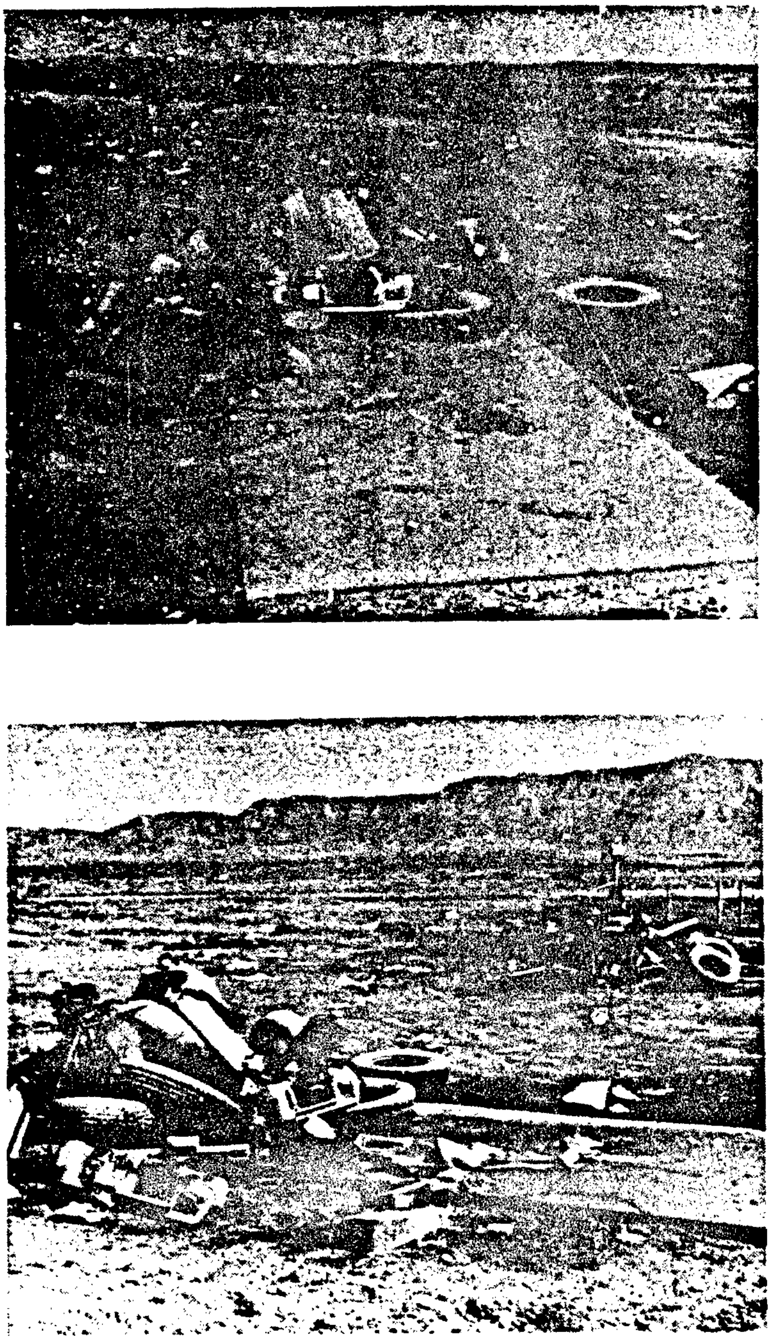


Fig. 2-3. Posttest Photographs of Experiment 4100-A.

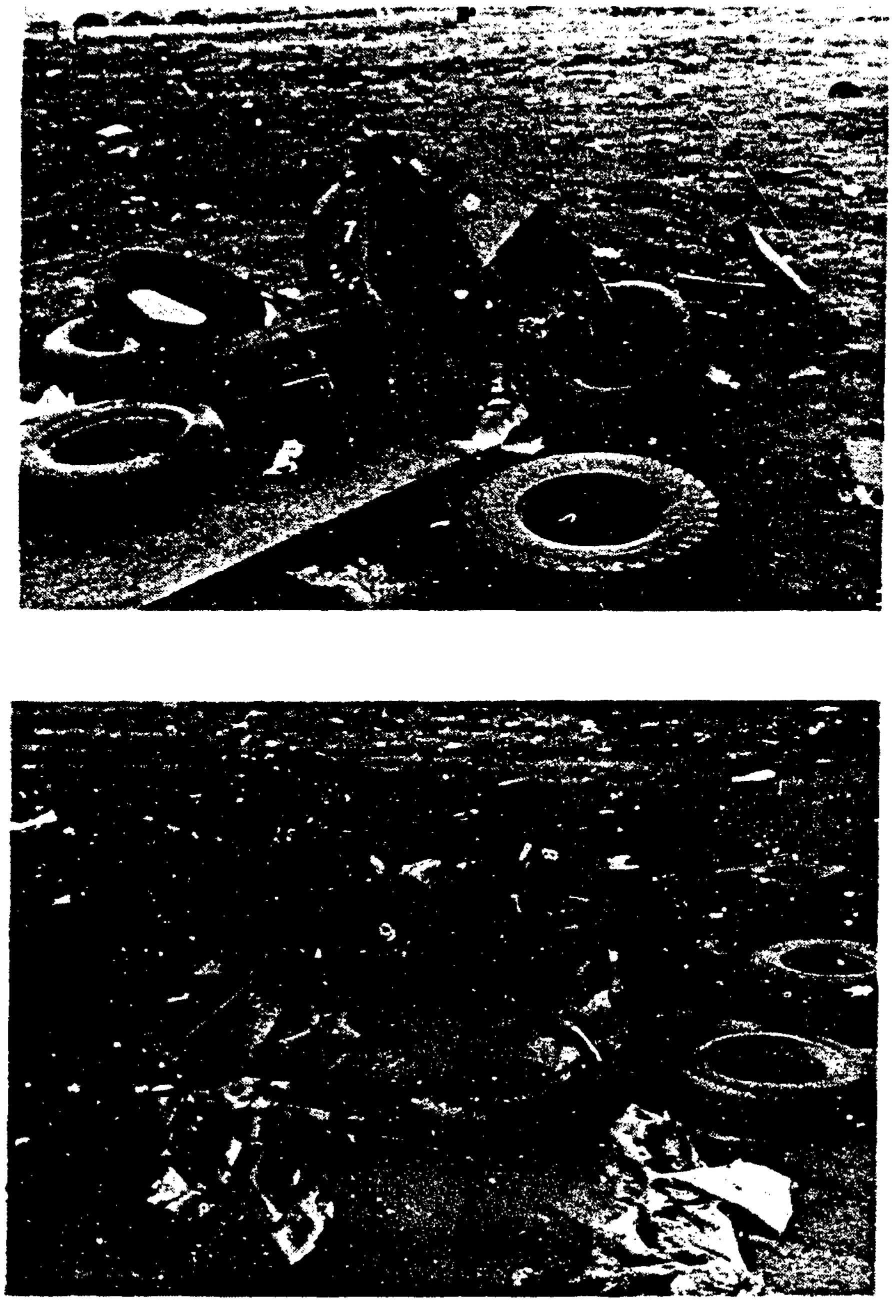


Fig. 2-4. Posttest Photographs of Experiment 4100-A.

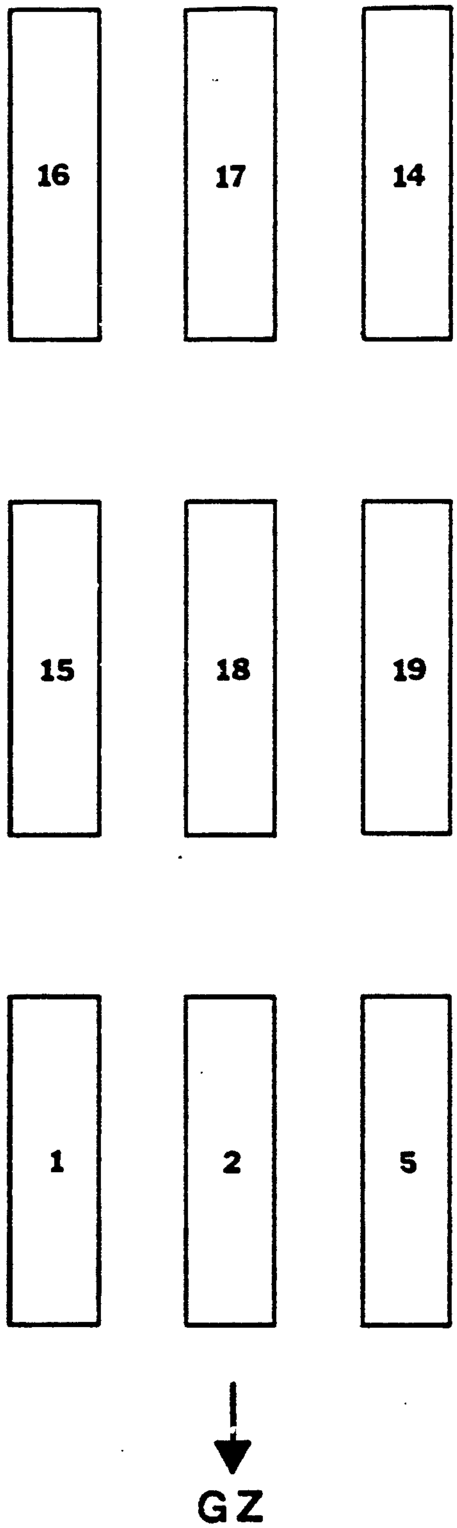


Fig. 2-5. Sketch Showing Location of Each Piece of Equipment in Experiment 4100-B.

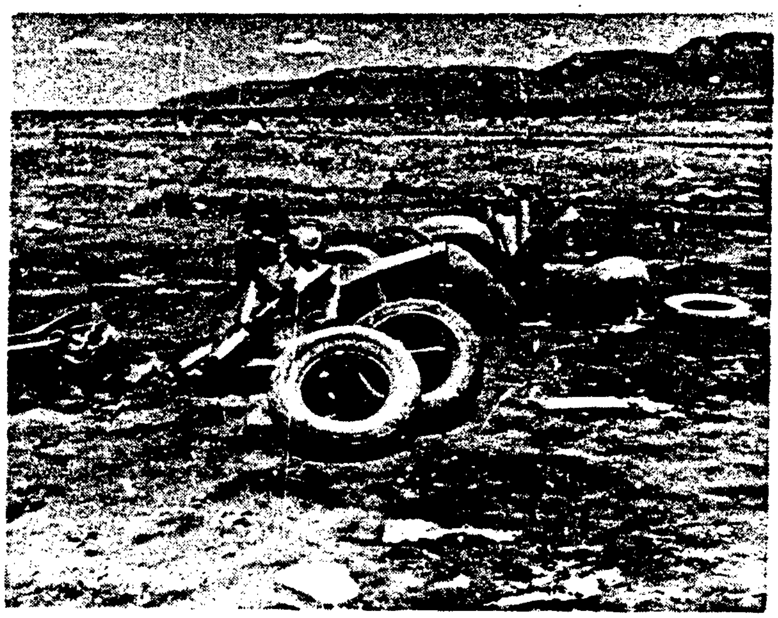


Fig. 2-6. Posttest Photographs of Experiment 4100-B.

4110: Equipment Cluster in WES Building

A third cluster was installed in the WES structure (DNA No. 7030) at the expected 25 psi range. The purpose of this test was to determine the effect of debris (in this case asbestos siding) on clustered equipment. The same kind of array as was exposed in the open was used, but plywood buffering was placed around and on top of the cluster and held in place with strapping. Pretest photographs of this cluster are shown in Figures 2-7 and 2-8.

The overpressure received at the building was 27 psi. The structure collapsed as shown in Figure 2-9. The cluster displaced approximately the same distance as those exposed in the open, but unfortunately this put it under one of the major structural members of the collapsing building. The resulting mess is shown in Figures 2-10 and 2-11. In spite of the apparent heavy damage, three of the saws were easily repairable. The posttest condition of each of the items along with the repair time is presented below.

Number	Condition	Minutes to Repair
23	Scrap	na
24	Scrap	na
25	Scrap	na
26	Good	21.0
27	Good	16.0
28	Scrap	na
29	Fair	55.0
30	Scrap	na
31	Scrap	na

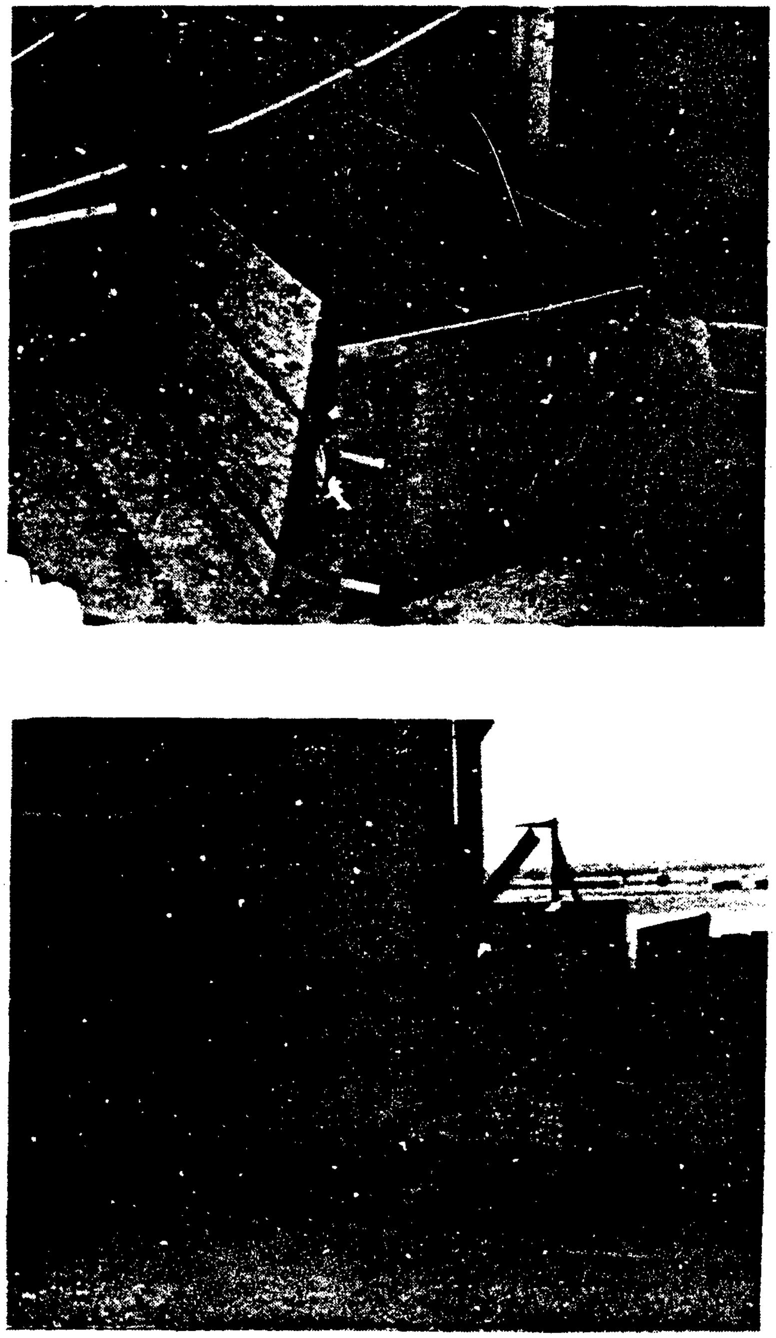


Fig. 2-7. Pretest Photographs of Experiment 4110 Inside WES Building.

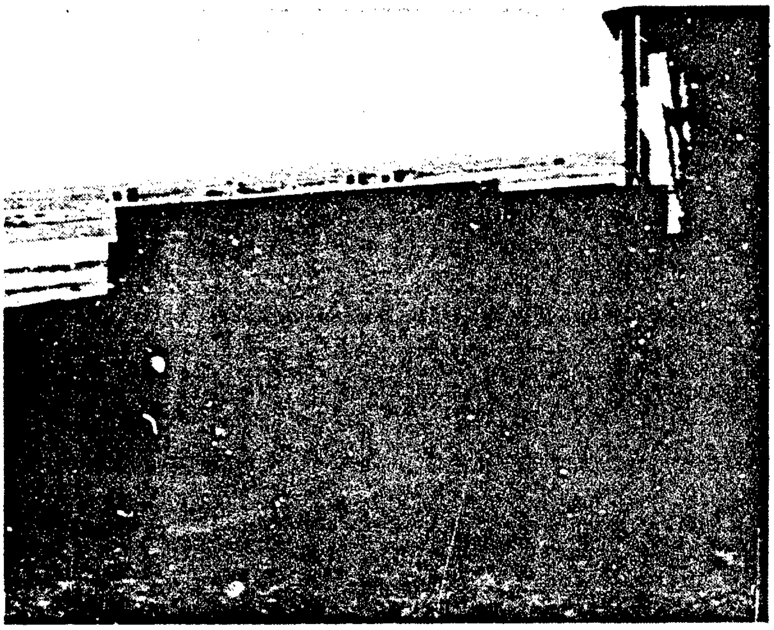


Fig. 2-8. Pretest Photograph of Experiment 4110 Inside WES Building.

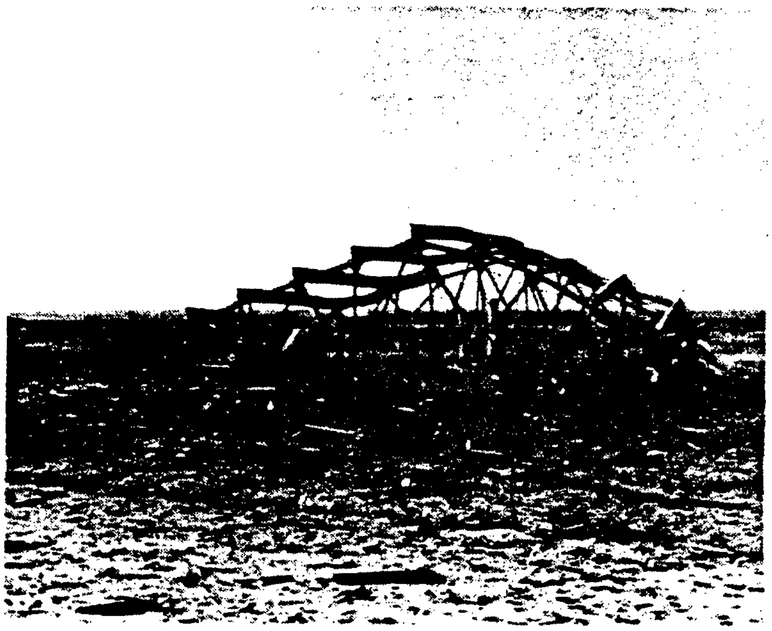


Fig. 2-9. Posttest Photographs of Collapsed WES Building.

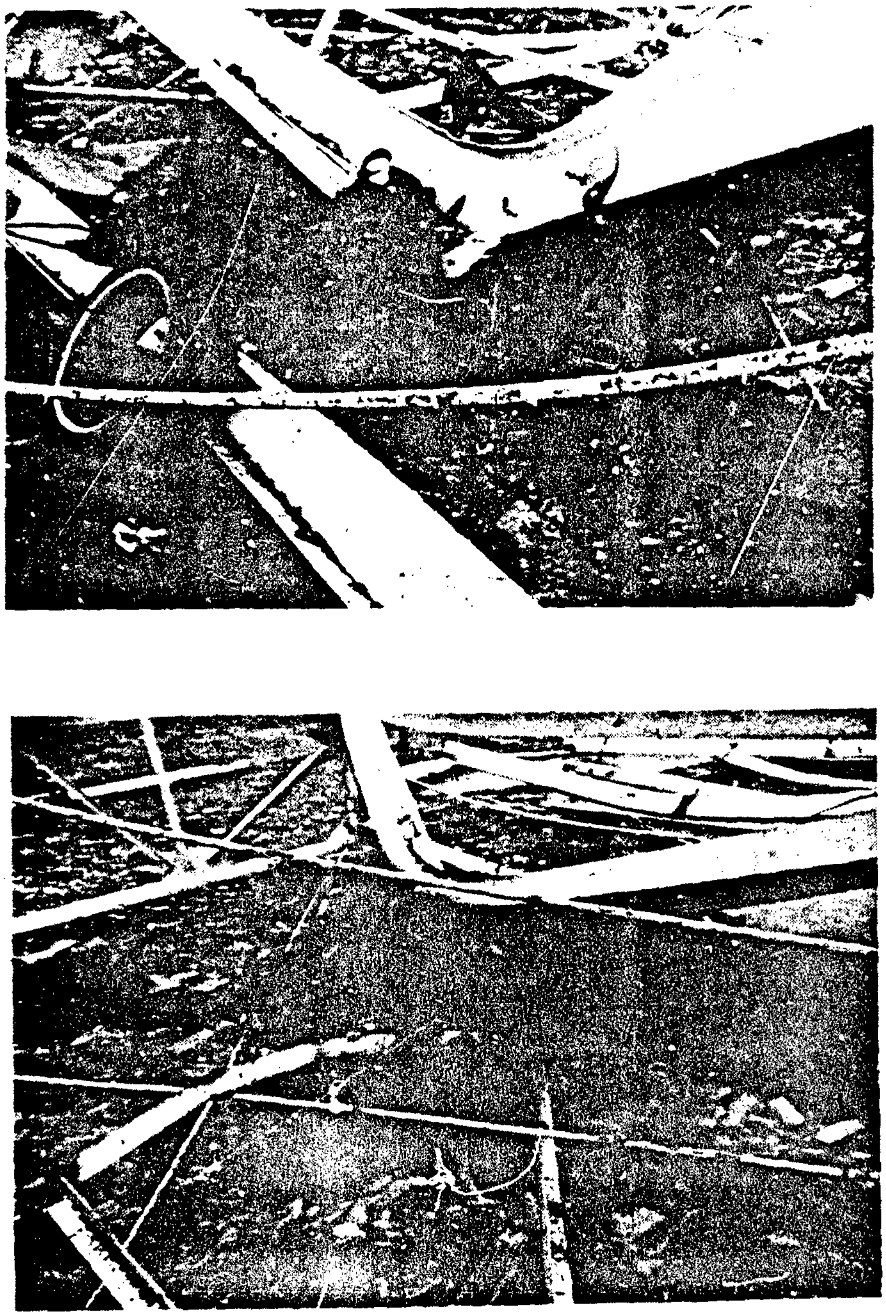


Fig. 2-10. Posttest Photographs of Experiment 4110.

Fig. 2-11. Posttest Photograph of Experiment 4110.

DNA Nos. 4115, 4120, and 4125 - SIMULATED EQUIPMENT CLUSTERS

A total of 13 arrays of simulated items of equipment, in this case 55-gallon drums filled with water, were arranged in clusters of various sizes and placed at expected overpressure ranges of 20, 30, and 40 psi. The purpose of these tests was to obtain additional data on clustering as a technique for hardening of industrial equipment at higher overpressures than previously proven, to investigate a range of banding materials of lesser strength at the 20 psi overpressure range where clustering had been previously proven, and to obtain high-speed camera coverage to obtain measures of array velocities and to observe how the arrays respond on different surfaces. Thus, these tests were an extension of a series conducted during the MILL RACE event, Ref. 1.

4115: Simulated Equipment Clusters at the 40 psi Overpressure Range

There were four different clusters in this experiment: 4115-A, a seven-barrel cluster on a concrete pad; 4115-B, a seven-barrel cluster on a dirt surface; 4115-C, a 19-barrel cluster on a concrete pad; and 4115-D, a 19-barrel cluster on a dirt surface. All of these clusters were bound together with 8,000 pound tensile strength seatbelt webbing at the third points. Pretest photographs of these arrays are shown in Figures 2-12 (front array) and 2-13A. The distance from the charge to this experiment was 500 ft.

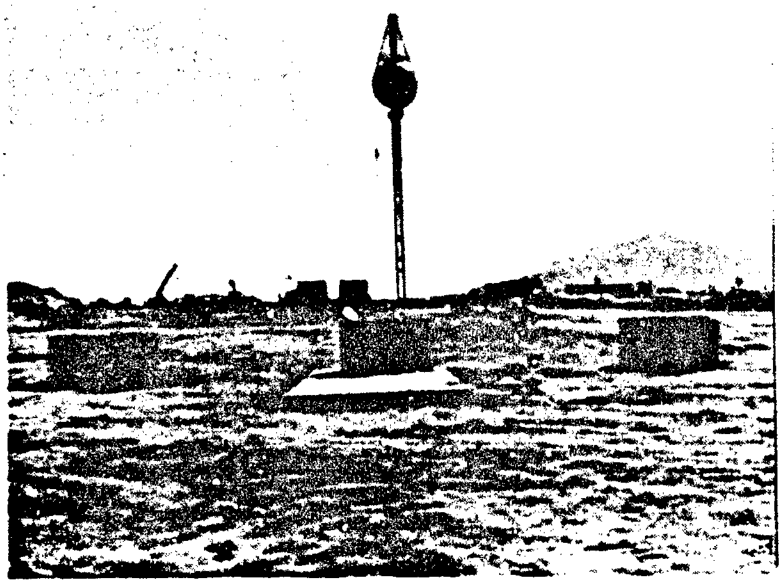
The estimated peak overpressure from the BRL northern instrumentation line was 44.31 psi. (The corresponding dynamic pressures at this location is not known.) As noted above, WES measurements made in front of this experiment indicate that the pressures may have been significantly higher, on the order of 20% to 30% higher. The damage to the arrays was extensive; at this overpressure all of the arrays broke up, and the individual drums were then subjected to the dynamic pressure as individual objects (negating the cluster concept over a major portion of the pulse). Breakup of the arrays occurred for two reasons: because some drum lids came off and let the drums deform as the fluids ejected, and because the seatbelt webbing ruptured where the drums did not deform. High-speed photography from farther down range show drums lofted as high as 30 to 50 feet in the air. For example, at the seven-barrel array on the concrete pad (4115-A), the seatbelt webbing ruptured

and the barrels were completely gone, as shown in Figure 2-13B, and many of the barrels from the other arrays at this ground range were found far down range. The ones that remained are shown in Figure 2-14. It is apparent from Figure 2-14A that the 19-barrel array on dirt (the most remote in the picture) was least affected, as expected.

It can be concluded from these results that the clustering concept involving barrels and strapping will probably not work at this high a dynamic pressure, so it would not be a practical method to apply to hazardous materials in drums. Applied to rigid equipment, however, the use of steel cabling or welded channels or I-beam might make clustering work even at this pressure level. As is discussed below and in Ref. 1, the method does work at lower overpressures, even for fluids in drums.

Fig. 2-12. Pretest Photograph of Experiment 4115.

A



B

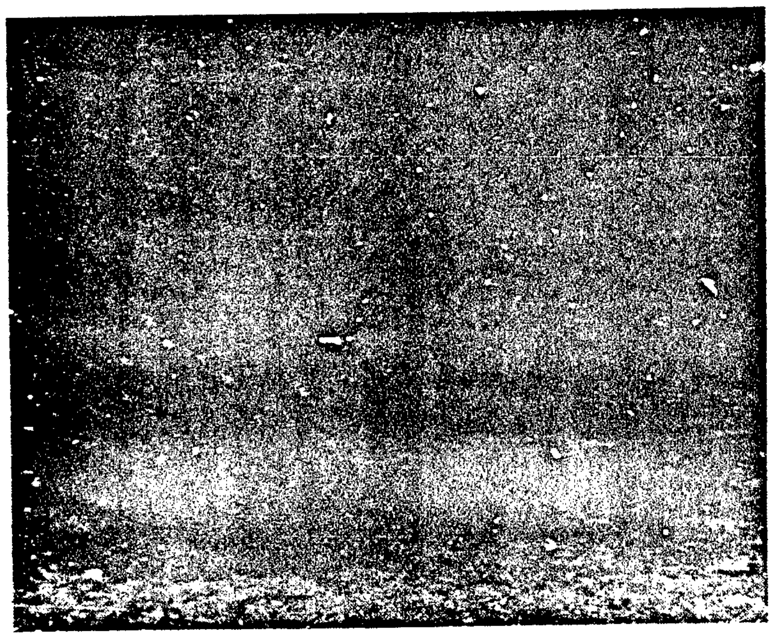


Fig. 2-13. Pre- and Post-Test Photographs of Experiment 4115.

A

B

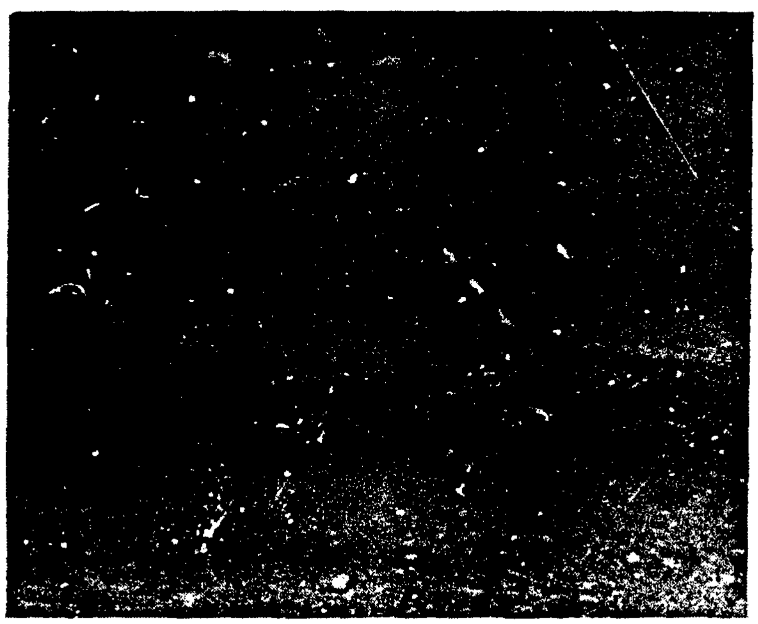


Fig. 2-14. Posttest Photographs of Experiment 4115.

4120: Simulated Equipment Clusters at the 30 psi Overpressure Range

There were five different clusters in this experiment: 4120-A, a 10-barrel cluster on a concrete pad; 4120-B, a 14-barrel cluster on a dirt surface; 4120-C, a 14-barrel cluster on a concrete pad; 4120-D a 10-barrel cluster on a dirt surface and 4120-E, a seven-barrel cluster on a dirt surface. These clusters were also bound together with 8,000 pound tensile strength seatbelt webbing at the third points. Pretest photographs of these arrays were shown in Figure 2-12 (2nd row of arrays back). The distance from ground zero to this experiment was 600 ft.

The estimated overpressure based on the BRL northern instrumentation line was 38.82 psi and the horizontal dynamic pressure was 23.7 psi. (The horizontal dynamic pressure impulse was 0.776 psi-s.) As noted above it is expected that the loadings at the experiment location may have been somewhat higher than that indicated by the gauge line. The array movement at this range was less severe than at the 40 psi range, as shown in Figures 2-15 and 2-16, but the drums were severely crushed here as well. The arrays all suffered some degree of breakup, in this case always due to drums losing lids and deforming so that the webbing loosened and released additional drums from the cluster. In array 4120-D, most of the array stayed intact even though two of the drums partially deformed after losing their lids (see farthest array in the upper picture of Figure 2-15). This suggests that rigid bodies can be successfully clustered at this pressure level and bound with 8,000 lb tensile strength seatbelt webbing, successfully. However, successful clustering of hazardous materials in drums would be very dependent on all the drums in an array remaining sealed so that integrity of the array was not lost through deforming of any of its members.

It can be concluded that, at this overpressure level, rigid body items can be successfully clustered and bound with 8,000 pound seatbelt webbing. Fluid filled drums may also be successfully clustered at this pressure level providing the drums maintain their integrity and stay sealed.

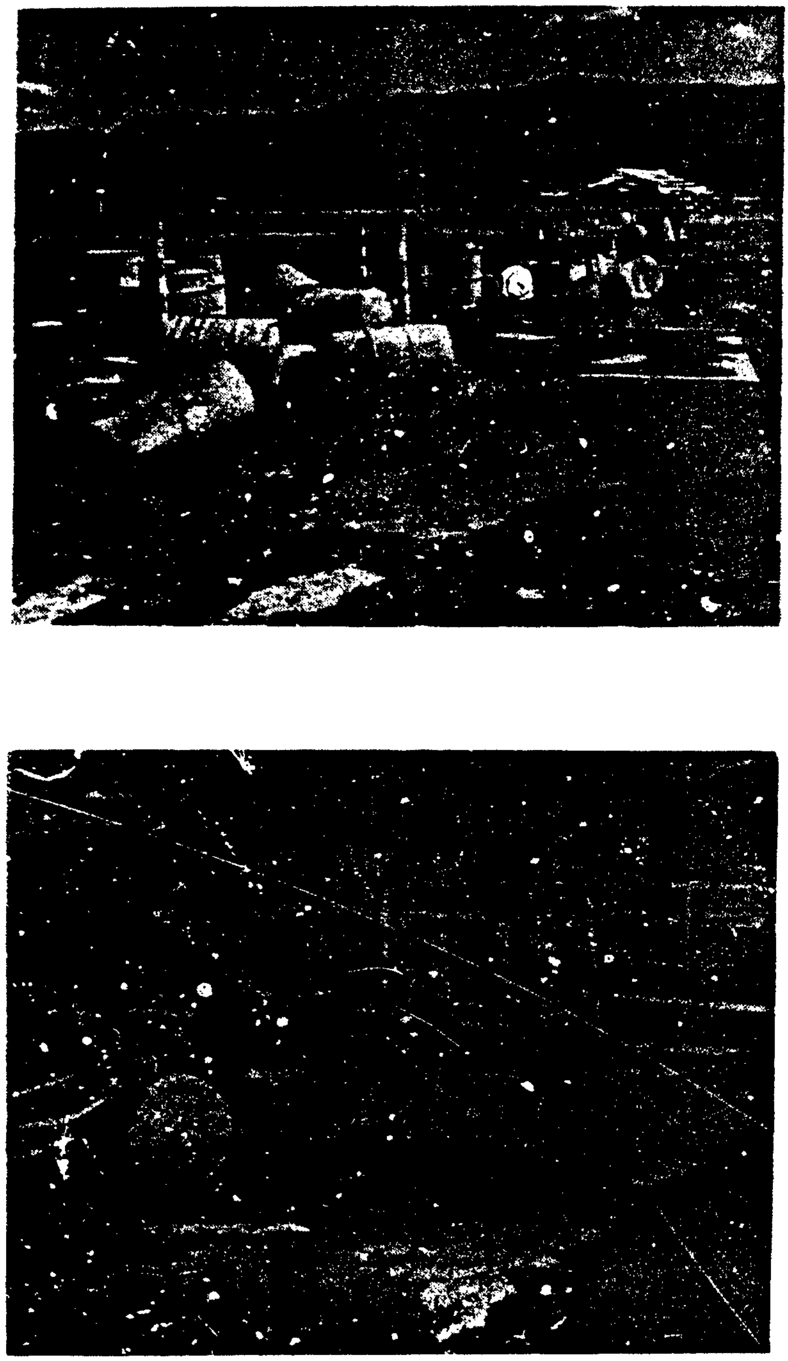


Fig. 2-15. Posttest Photographs of Experiment 4120.

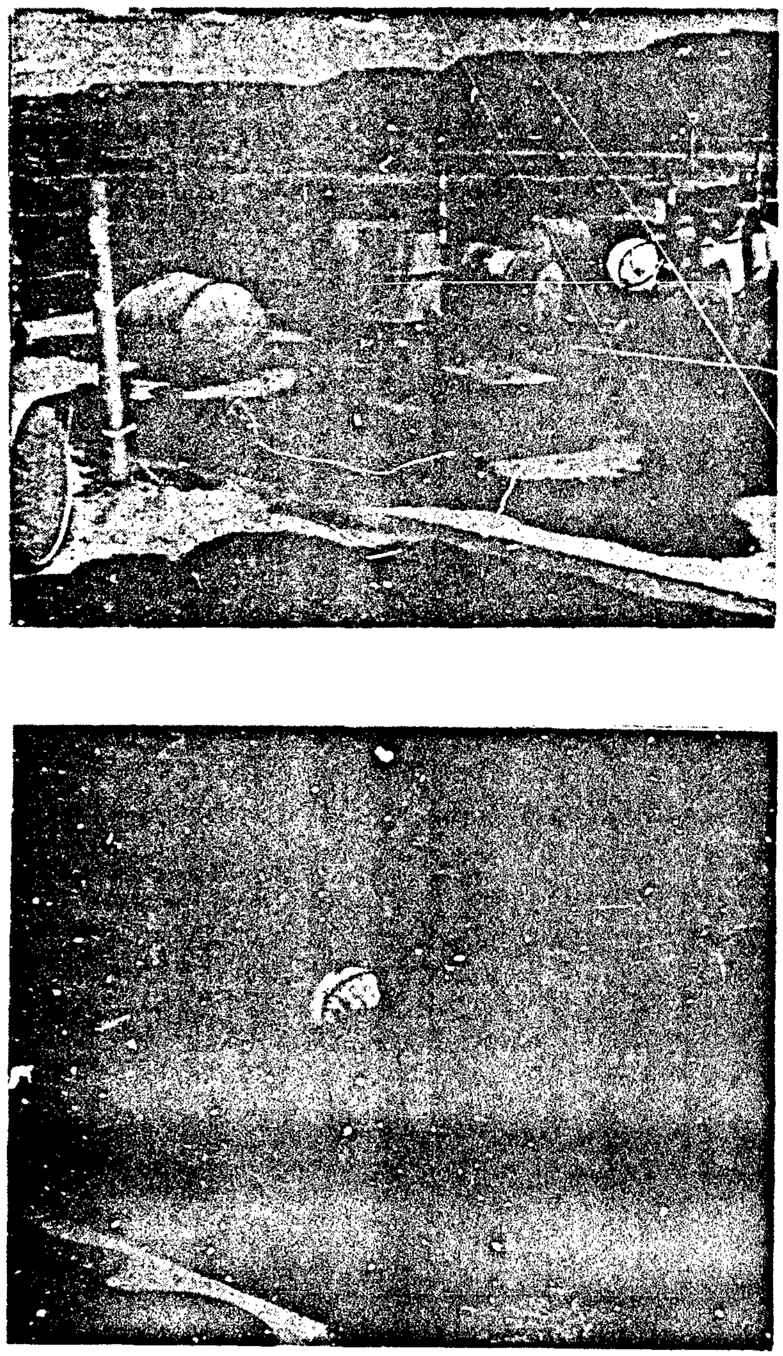


Fig. 2-16. Posttest Photographs of Experiment 4120.

4125: Simulated Equipment Clusters at the 20 psi Overpressure Range

There were three clusters in this experiment (and one single drum left over that was exposed by itself): 4125-A, a seven-barrel cluster on dirt bound at the third points with 1,000 pound tensile strength nylon cord, and having a single barrel attached via 6,000 pound seatbelt webbing at the mid-point to the farthest barrel in the array down range; 4125-B, a seven-barrel cluster on a concrete pad bound at the third points with 700 pound tensile strength nylon cord; 4125-C, a seven-barrel cluster on dirt bound at the third points with 4,000 pound tensile strength seatbelt webbing and having a single barrel attached via 6,000 pound seatbelt webbing at the mid-point to the farthest barrel in the array down range. A pretest photograph of these arrays is shown in Figure 2-17. The distance from ground zero to this experiment was 740 feet. (The significance of the extra drums attached to the arrays on dirt will be described later.)

The estimated peak overpressure based on the BRL northern instrumentation line was 23.22 psi. No WES measurements were made at this ground range. Neither of the nylon cord bindings was adequate to hold an array together at this pressure level, but the 4,000 pound seatbelt webbing was (see Figure 2-18). The figure also shows that the cluster on dirt that remained together moved only 1 foot. Much less motion occurs on a dirt surface, because the static overpressure forces the drum edges into the soil and helps to hold them in place against the dynamic pressure.

It can be concluded that 1,000 pound tensile strength binding at the third points is inadequate at this pressure level, but that 4,000 pound tensile strength binding will be adequate for clusters of this size. Figure 2-18 also indicates that some of the lids came off 4125-C, the array on dirt that remained clustered. It is possible this could affect how the array responds, but no high-speed photographs were available to show when this happened with respect to the passage of the pulse. Thus, additional experimentation would be required to determine whether Mt size explosions would seriously damage this type of array on soil. The response will be dependent on when the static overpressure drives the drum edges into the soil relative to passage of the pulse. It would be extremely valuable to compare this at two scale sizes to see if development of stability simply takes a constant time or if it scales with weapon size.

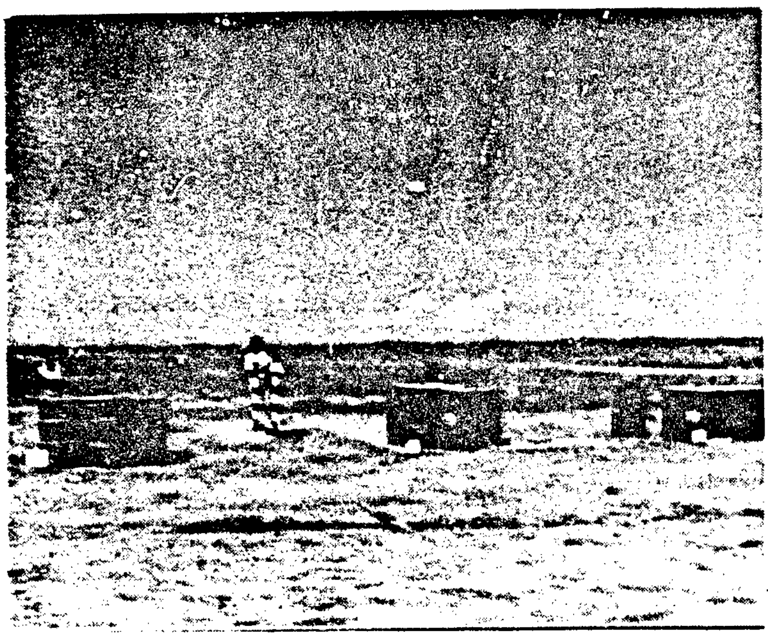


Fig. 2-17. Pretest Photograph of Experiment 4125.

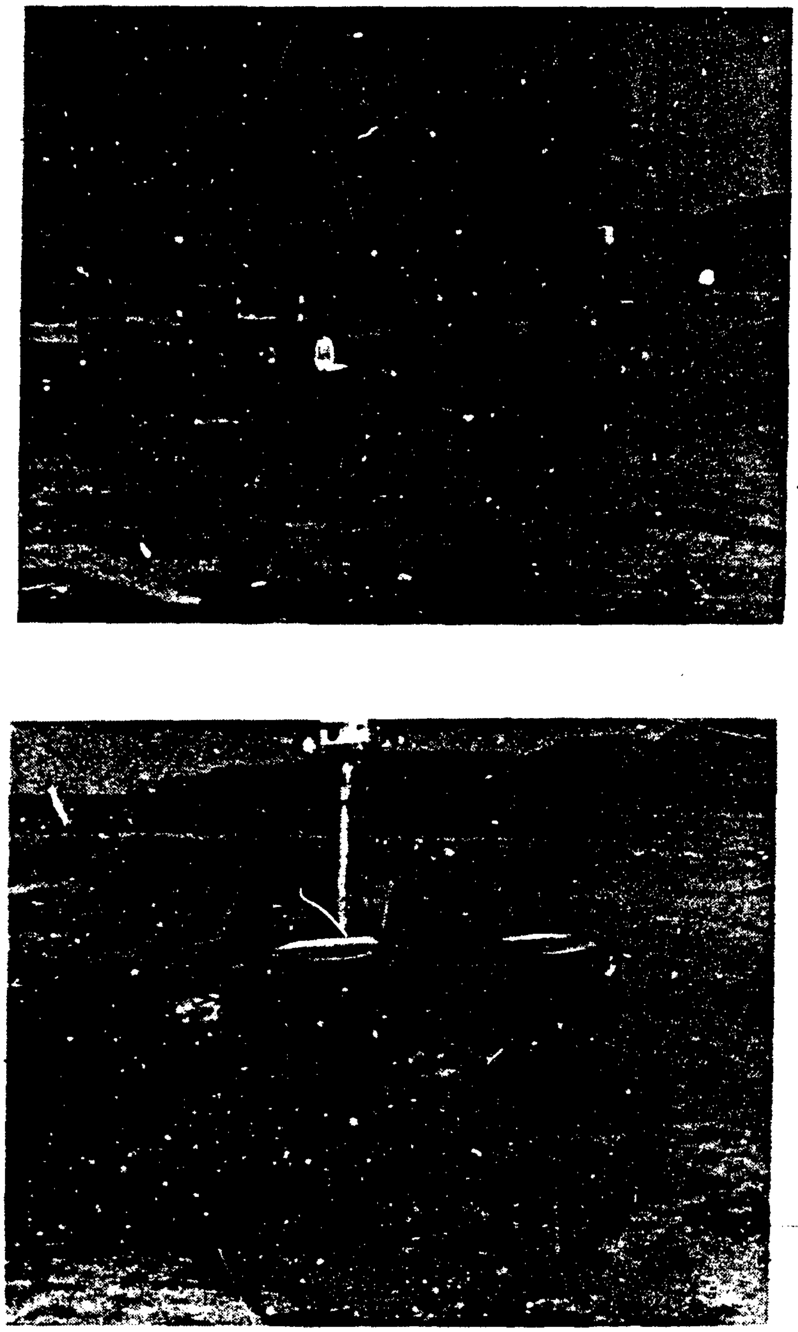


Fig. 2-18. Posttest Photographs of Experiment 4125.

DNA No. 4130 - UNHARDENED ITEMS OF EQUIPMENT

Eight items of equipment were placed individually at an expected overpressure range of 20 psi. The purpose of this test was to obtain reference data on vulnerabilities of equipment (i.e., items tested in hardening experiments) when exposed without hardening of any sort. These experimental items consisted of four bandsaws, two table saws, and two electronic power supplies (for operating microwave tubes). Two of the bandsaws were placed side on to the blast and two were placed end on; the table saws presented essentially the same profile at right angles, so they were placed with the same face parallel to the wave front. The electronic power supplies were roughly 5 X 8 X 17 inches and were placed with one oriented so that the 5 inch X 17 inch face was parallel to the wave front and the other with the 8 inch X 17 inch face parallel with the wave front. A pretest photograph of some of these items and a sketch of the entire array are shown in Figure 2-19.

The estimated peak overpressure from the BRL northern instrumentation line at this range was 23.22 psi and the horizontal dynamic overpressure was 10.1 psi. For the most part, the individual items of equipment were all badly damaged or demolished, excepting the bandsaws that were oriented end on to the blast wave. Figure 2-20 (upper photo) corresponds to Figure 2-19, but looking down range from the initial location of item C. In this photograph, items B, C, and D can be seen. Item C, the table saw, is far down range (120 feet), while just in front and to the right of it (in the photo) is item D, the No. 3 power supply, at a distance 80 feet down range. In the middle of the photo is item B, the side on bandsaw, which is in three pieces located at distances of 25 to 38 feet down range. Two of these pieces are shown in the foreground (right and left side) of the lower photo. In the background to the left and front of item 4100-B (the array of 9 bandsaws on a dirt surface) can be seen item 4130-A at a distance of about 15 feet down range from its starting position.

Many of the individual items of experiment 4130 can also be seen in the far field of Figure 2-6 (lower photograph). Item 4130-A (marked "10") can be seen just behind the array in the foreground, while slightly behind it and to the left (in the

photo) is one part of item 4130-B, and in the far field behind that is item 4130-H. To the right of that (nearer the edge of the photo) and closer in, is item 4130-E, while at about the same location near the left edge of the photo is item 4130-D.

Figure 2-21 shows item 4130-A, which was readily repairable with only a few minutes of work. Figure 2-22 shows two parts of the remains of items 4130-B, which was not repairable. The upper photo in Figure 2-23 shows item 4130-C, unrepairable (broken castings), while the lower photo shows item 4130-D, which had severe internal damage and was also unrepairable. Figure 2-24 shows item 4130-E, which was located 30 feet down range and suffered moderate internal damage, but was still not readily repairable. Item 4130-F can be seen about 20 feet down range from its starting point in the upper photo of Figure 2-25 and close up (in the lower photo). Although this bandsaw lost its sheet metal legs, it was repairable and usable in a matter of 10 minutes. Figure 2-26 shows three of the five pieces of item 4130-G found at various distances from 25 to 100 feet down range; the unit was unrepairable. Item 4130-H is shown in a closeup in Figure 2-27. This unit also was unrepairable.

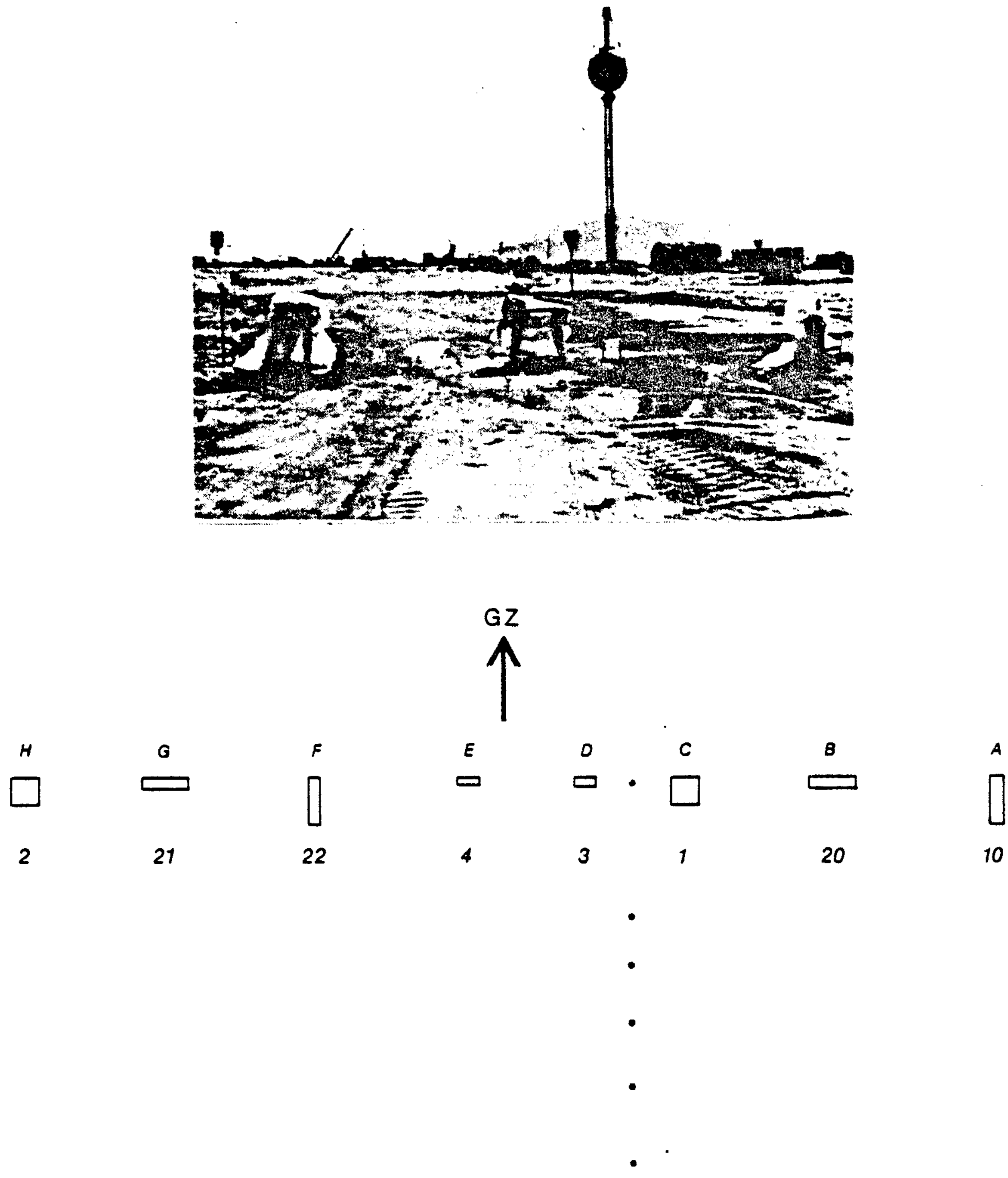


Fig. 2-19. Pretest Arrangement of Experiment 4130.

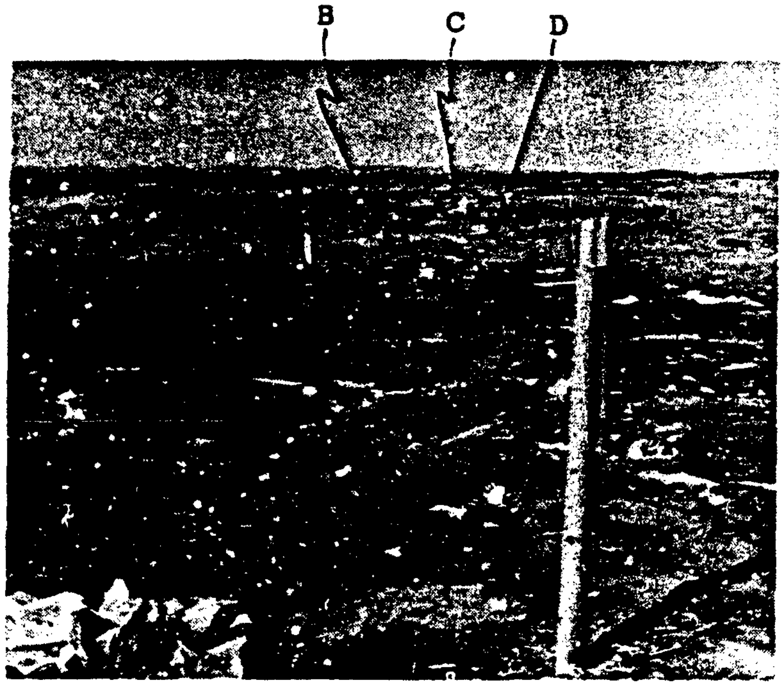


Fig. 2-20. Posttest Photographs of Experiment 4130.

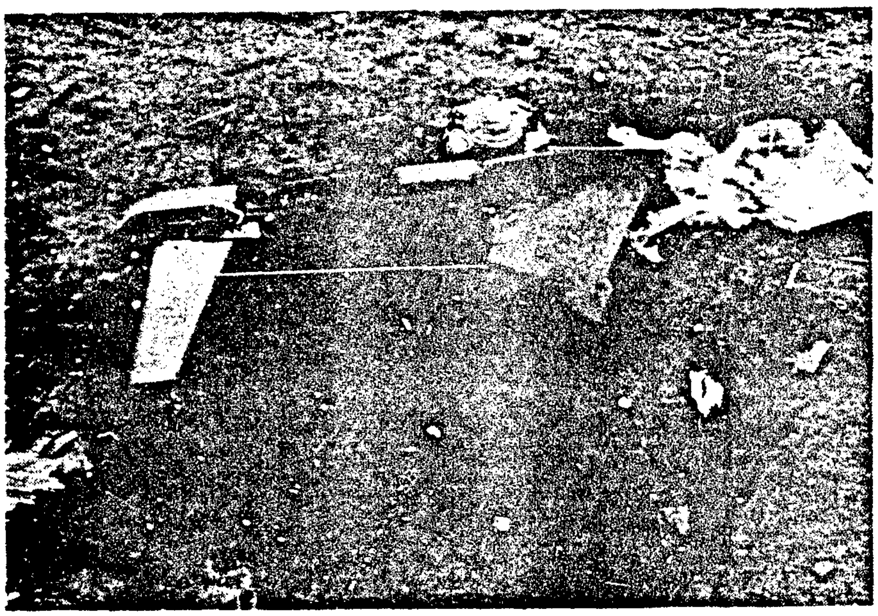
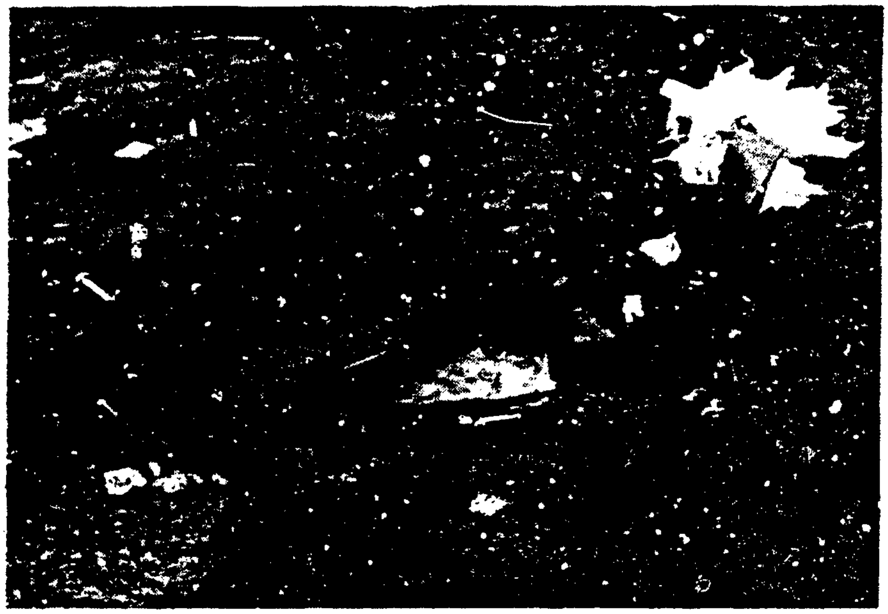


Fig. 2-21. Posttest Photograph of Item 4130-A, Readily Repairable.



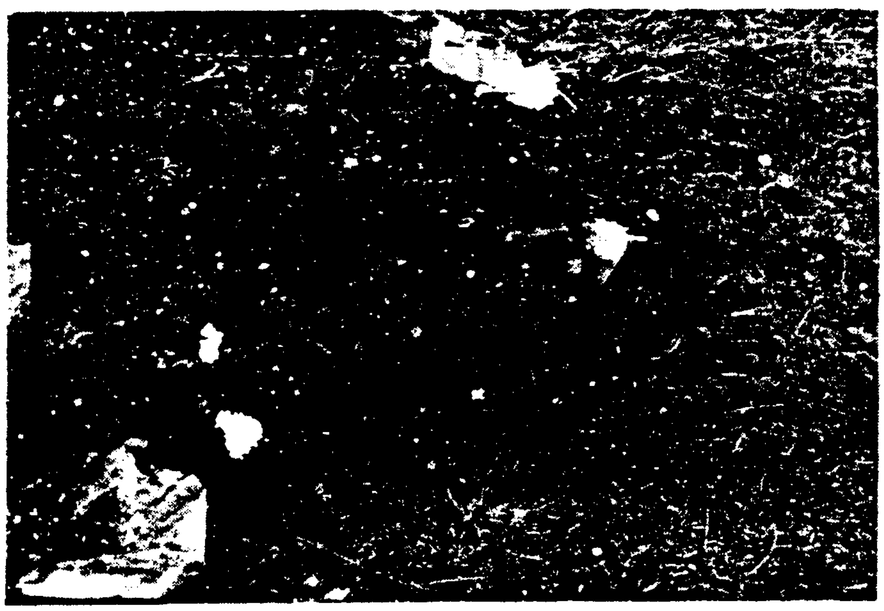
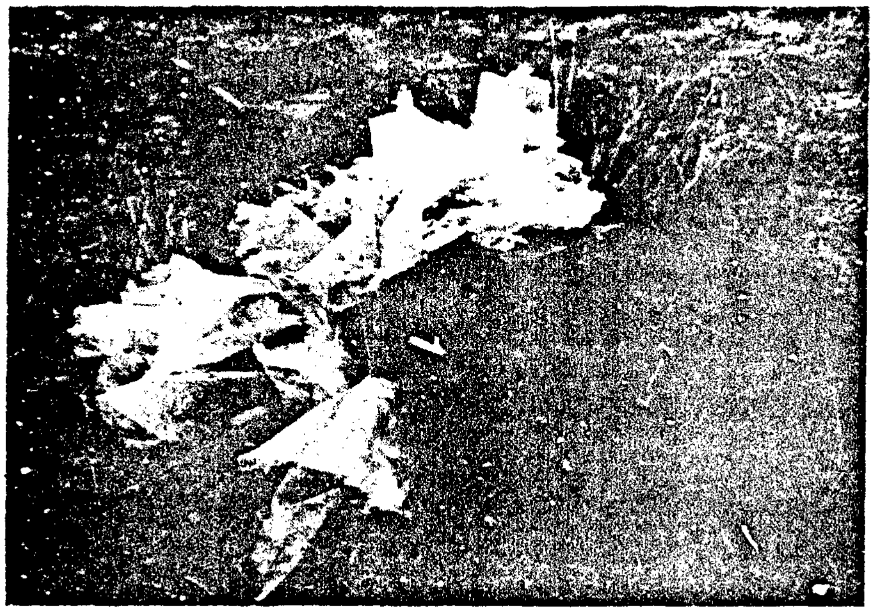


Fig. 2-22. Posttest Photographs of Item 4130-B, Not Repairable.



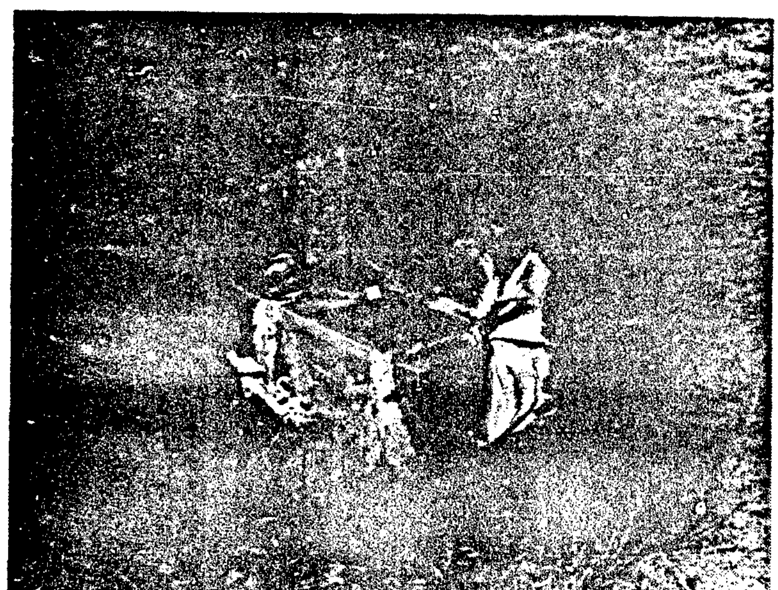


Fig. 2-23. Two Unrepairable Items, 4130-C and 4130-D.

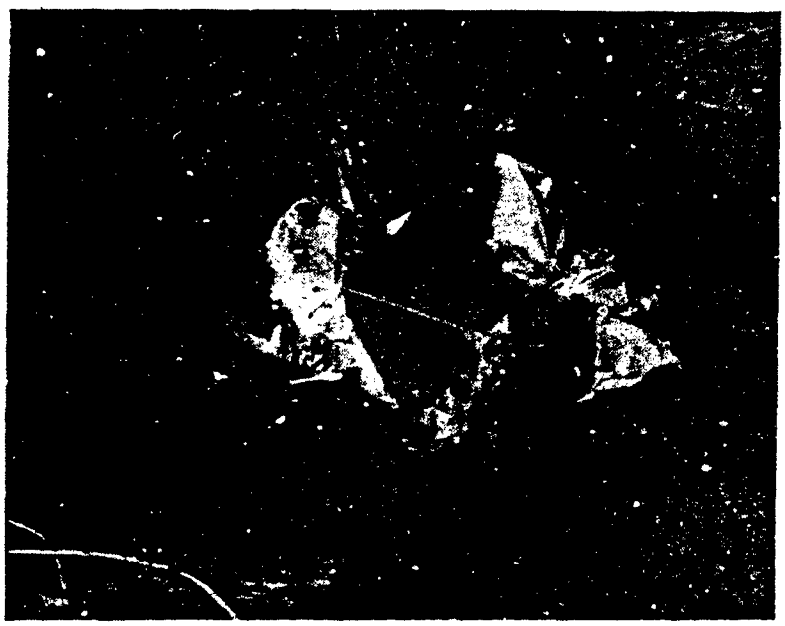


Fig. 2-24. Posttest Photograph of Item 4130-E, Located 50 Feet Down Range.

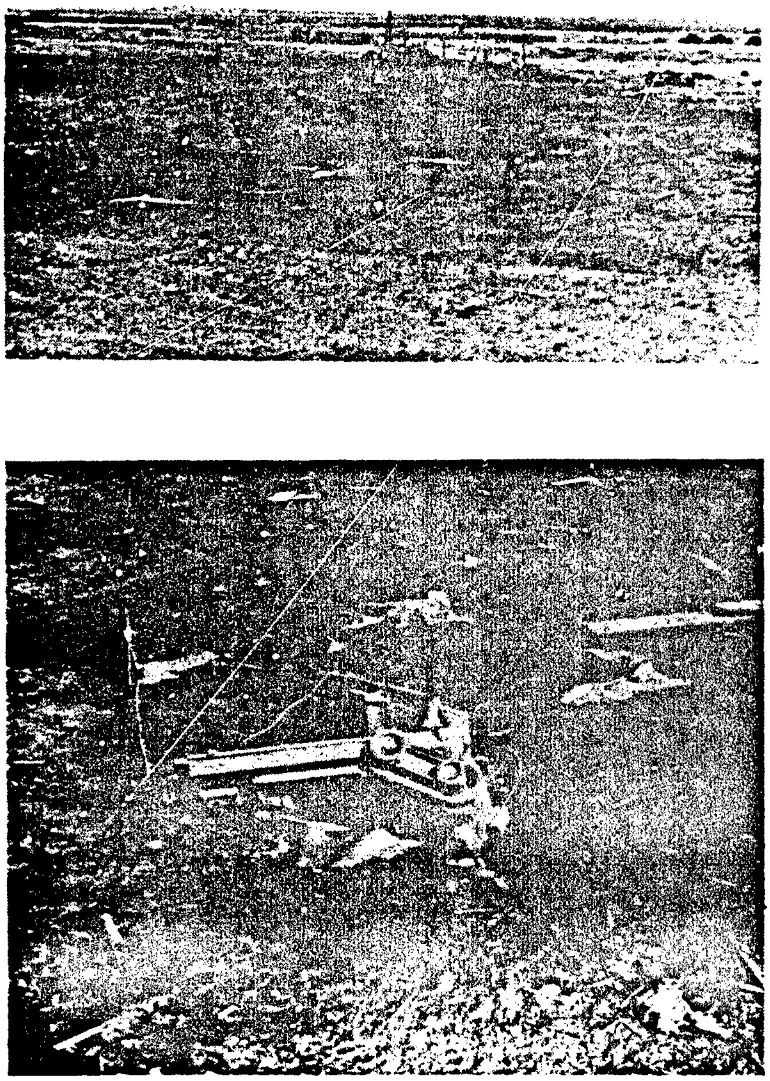
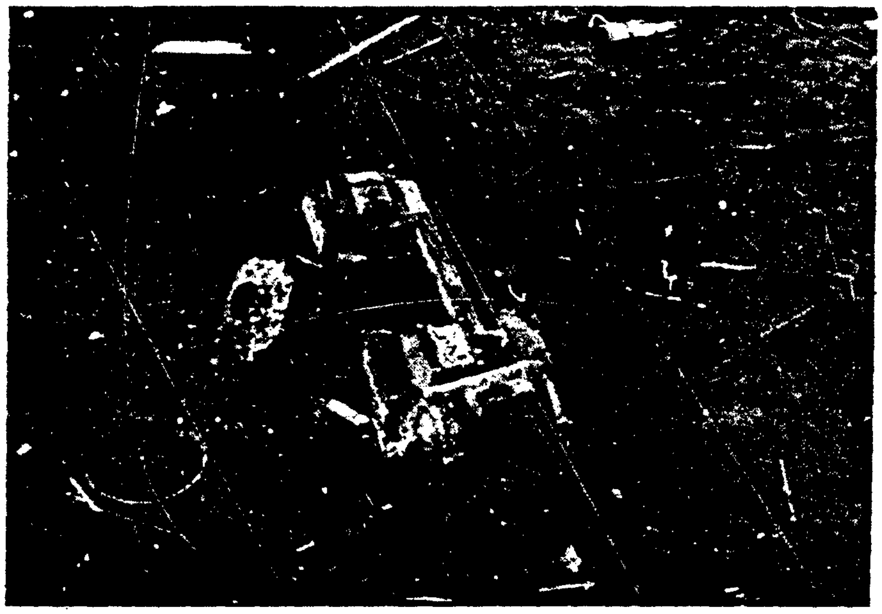


Fig. 2-25. Posttest Photographs of Repairable Bandsaw, Item 4130-F.



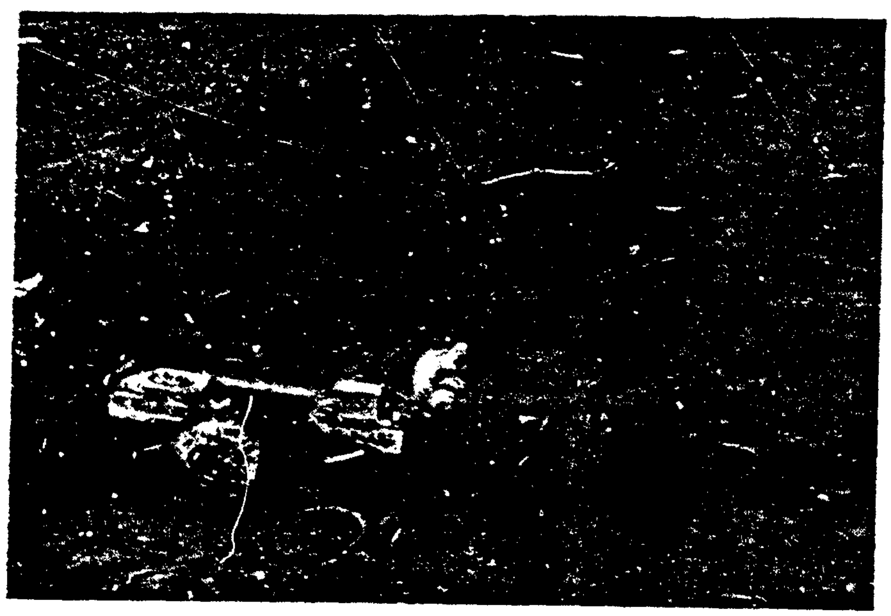


Fig. 2-26. Posttest Photographs of Remains of Item 4130-G.

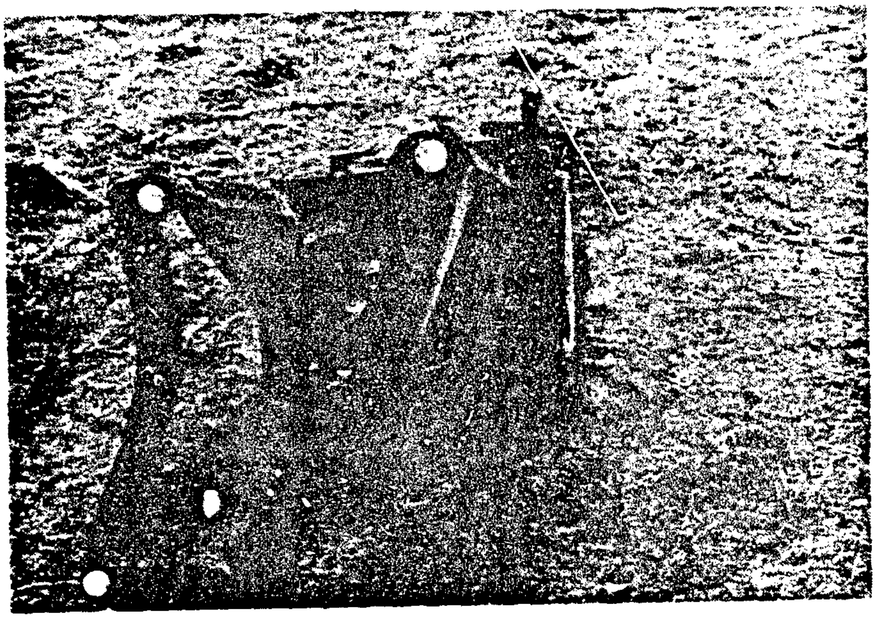


Fig. 2-27. Closeup of Unrepairable Item 4130-H.

ELECTRONIC POWER SUPPLY HARDENING EXPERIMENT

Two power supplies of the same type as items 4130-D and E were fielded at the expected 20 psi ground range and protectedr from the horizontal dynamic pressure, by placing them in the trailing drums of experiments 4125-A and 4125-C (see Figure 2-18). One of these was also given protection from the static overpressure by placing it in a bath of alcohol inside a plastic bag in a depression in sand that half-filled the trailing drum in experiment 4125-A, Figure 2-28 (upper photo). The other unit was not given any protection from the static overpressure; it was simply placed on top of the sand in the trailing drum of experiment 4125-C, Figure 2-29 (upper photo). The lower photographs in these two figures show the posttest condition of the two power supply units. No physical damage was suffered by the unit submerged in alcohol, and it tested out as undamaged functionally. Some physical damage was suffered by the unit subjected to the static overpressure (see lower photo in Figure 2-29); it was functional, but required minor repairs that took a matter of a few minutes. Thus, this experiment suggests that delicate electronic equipment could be hardened to 20 psi in a period of hours.

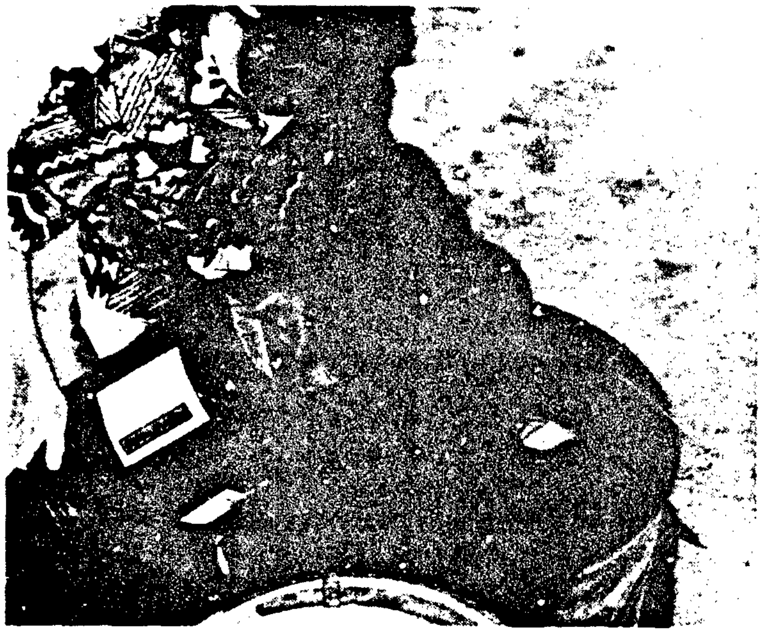


Fig. 2-28. Pre- and Post-Test Photographs of Electronic Power Supply Hardening Experiment.

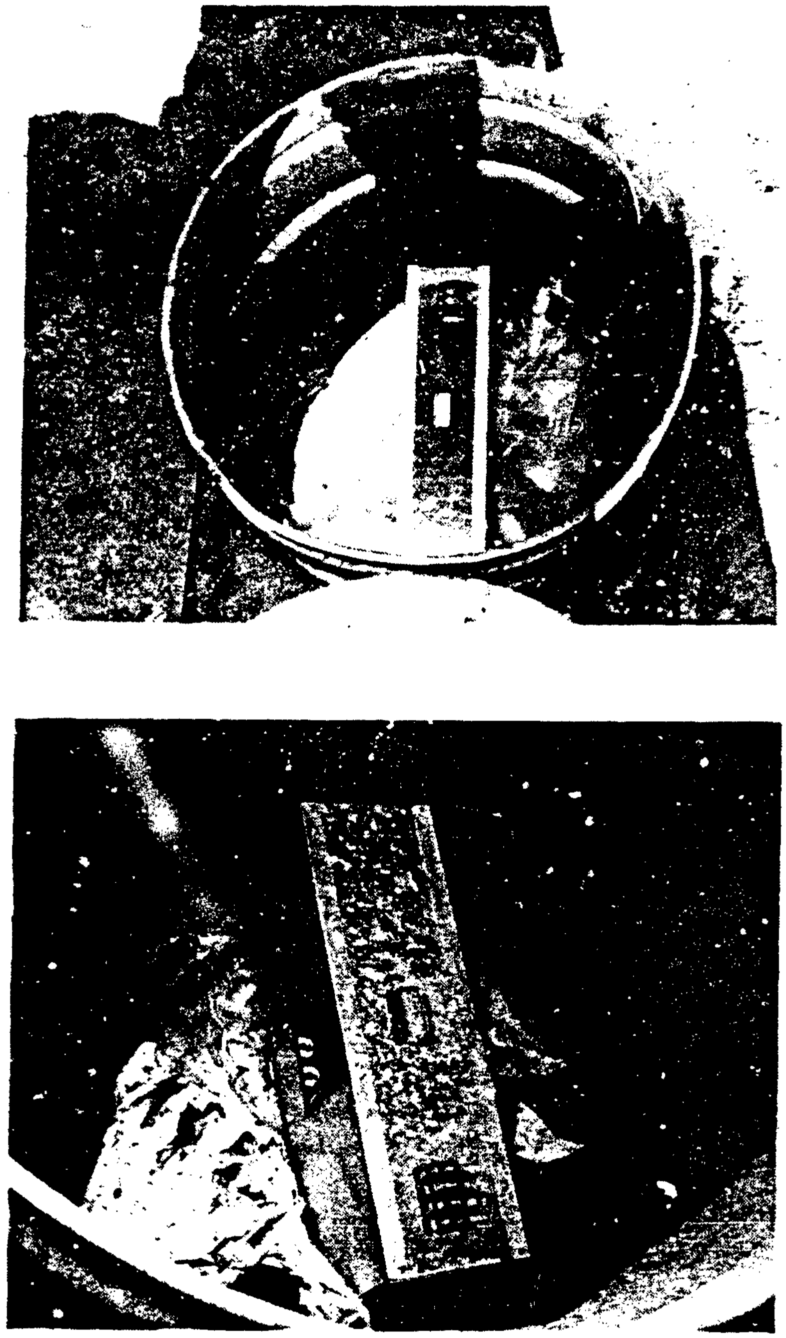


Fig. 2-29. Pre- and Post-Test Photographs of Electronic Power Supply Hardening Experiment.

Section 3
BASIC SHELTER DESIGN CRITERIA EXPERIMENTS
DNA Nos. 4140 and 4145

INTRODUCTION AND OBJECTIVES

In support of the FEMA programs to develop criteria for risk area key worker shelters, two one-fifth scale model high rise structures were exposed at the 50 psi range. The objectives of these experiments were to: gather experimental data on frame response; test the basement walls under more realistic conditions where the blast wave reflects off the front of the building (which would increase the loading on the soil and hence on the basement walls); obtain debris distribution data to supplement both the analytical and experimental work being conducted by SSI; and finally, to supplement data obtained in a building collapse program recently conducted by SSI, Ref. 3. The data will also be valuable for development of criteria for the upgrading of existing structures as shelters, as described in Ref. 4, and the siting of special purpose key worker shelters that are planned for implementation over the next few years.

DESIGN CRITERIA

This experiment was an extension of work on high rise structures, which has been underway at SSI over the past few years. This previous work has included a study reported in "The Effects of Building Collapse on Basement Shelters in Tall Buildings," Ref. 3. The objective of this study was to determine if the results from explosively demolished buildings could be used to improve the current and future guidance on the development of key worker shelters in urban areas. The study involved an analysis of previously demolished buildings and participation in five building demolitions. This building collapse program was supplemented by an analytical effort reported in "The Analysis of the Effects of Frame Response on Basement Shelters in Tall Buildings," Ref 5. The objective of this program was to

develop a prediction technique for predicting the mode of collapse of high rise buildings under blast loading. The developed technique was tested using one of the previously demolished buildings from the building collapse program, the Continental Life (Peachtree) Building in Atlanta, Georgia. The results of this frame response program indicated that the predominant initial response of a blast loaded high rise building, particularly one with an upgraded basement, is at the first to second story level. This is illustrated in Figure 3-1, a computer prediction of the horizontal displacement of a failing high rise building and in Figure 3-2, a series of sketches of the predicted phases of structural failure of the Peachtree Building under blast loading.

Therefore, since most of the structural response of interest occurs at the first or second floor, it seemed reasonable that in DIRECT COURSE it would be possible to study high rise building response by using only the lower portion of the structure. Taking into account data requirements, scaling criteria, and shipping limitations, it was determined that a four story, one-fifth scale structure would accomplish most of the objectives of the program.

It should be noted that the buildings were not scale model buildings. They were treated as small buildings, designed and constructed using conventional materials that are available. For example, a D4 wire used in the manufacture of deformed welded wire fabric is almost precisely a one-fifth scale of a No. 9 reinforcing bar. Rather than trying to specify and use micro-concrete, which is used in model studies, actually a scaling of the aggregate to one-fifth scale was used and a relatively conventional concrete mix developed and used. The intent here is that a future analysis could be made of this "conventional" small building and if the analysis could be developed that would predict the behavior of this small structure using conventional means, then one would suspect that the analysis and predictions made for full scale buildings should be reasonable. It is realized that there are a great many problems in small scale concrete structures and that scaling as such is very difficult.

The full scale floor system was designed for a live load of 125 psf, which is a conventional live load for the first and second floor of office buildings. This is also

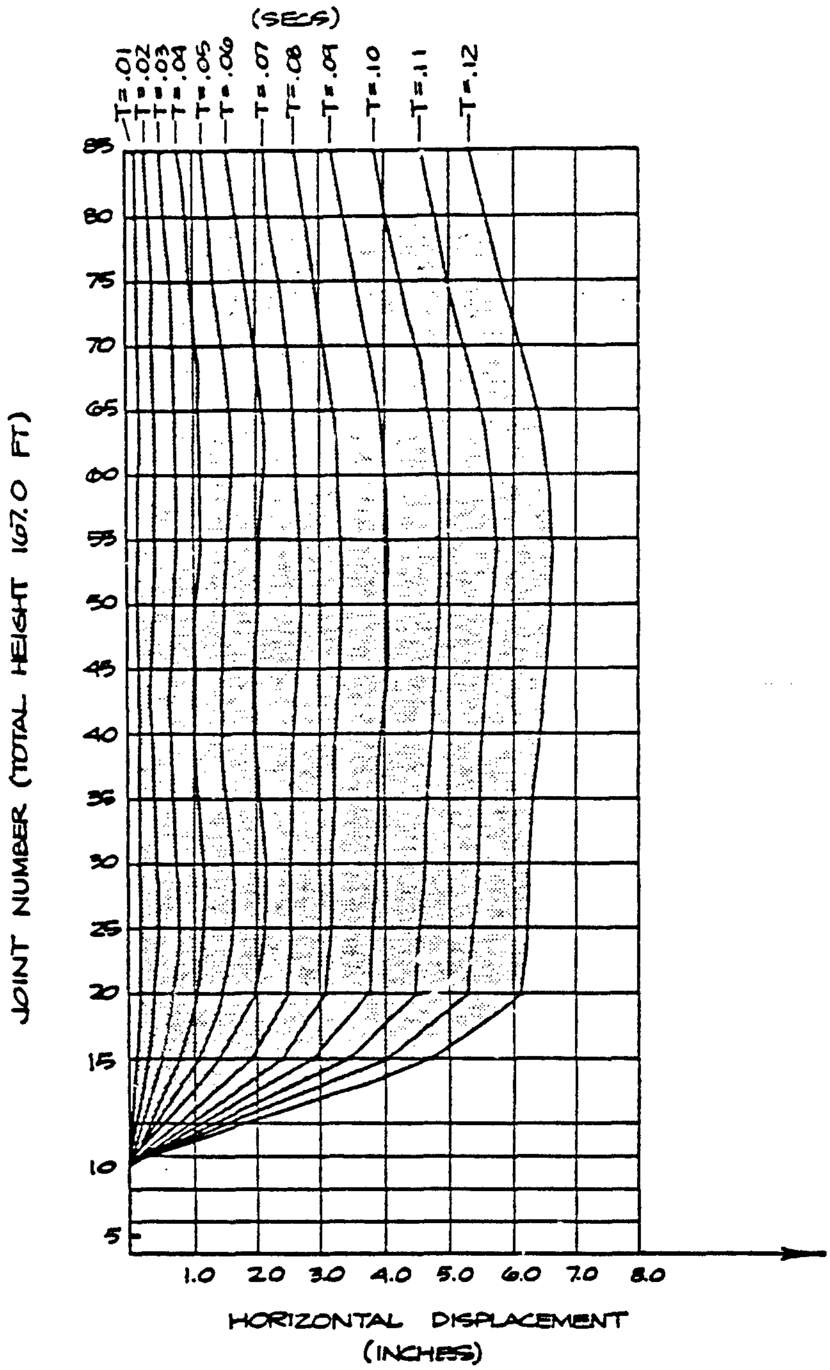


Fig. 3-1. Computer Prediction of Horizontal Displacement of a Failing High Rise Building (early time history to t = 0.12 s).

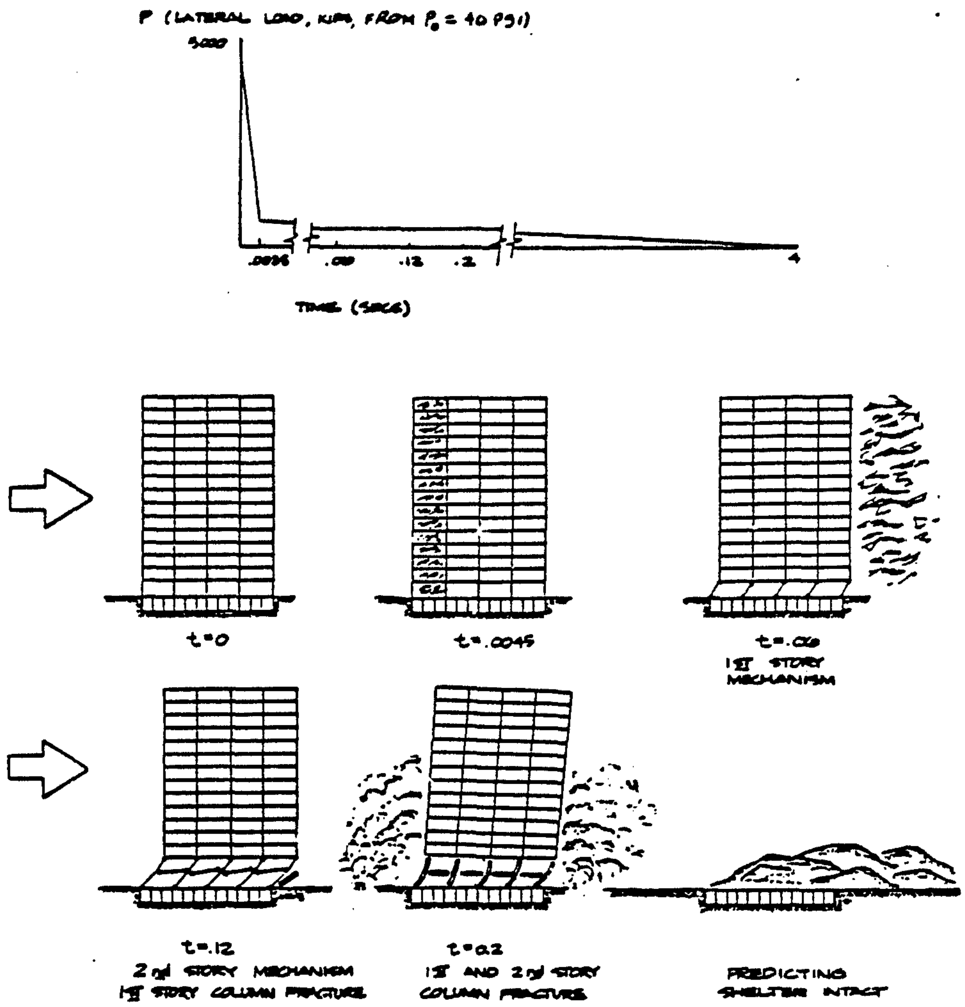
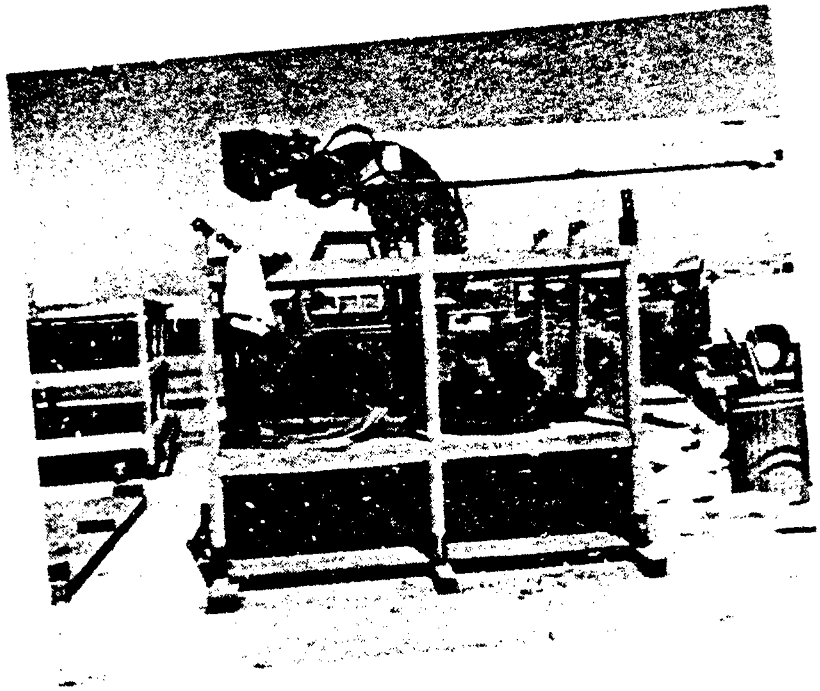


Fig. 3-2. Peachtree Building, Phases of Structural Failure.

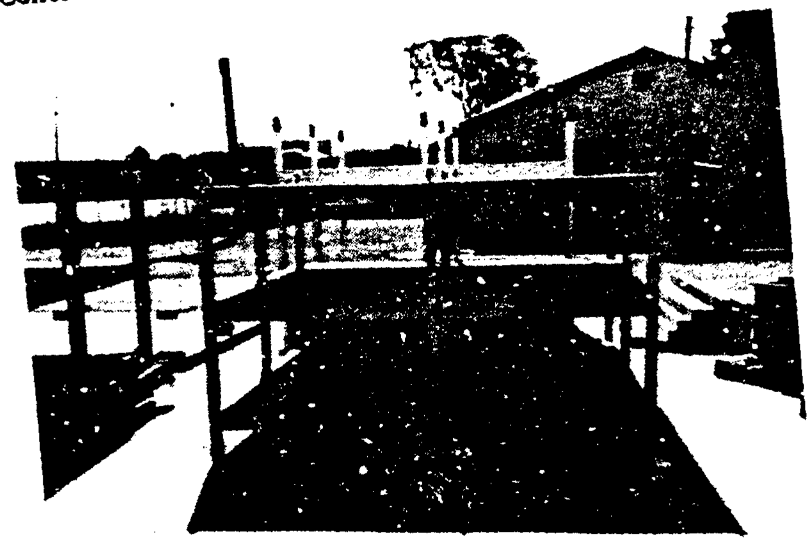
the load criterion used in designing the floor systems that were shored and exposed and that survived at the MILL RACE event in the basement structures. The shoring plan used in the basements of these model structures was one that had been proven successful in a full scale experiment of a beam/slab/girder floor at the MILL RACE event at the 40 psi level. Analytically, the floor system was somewhat marginal at the 40 psi event, but it behaved very successfully at MILL RACE, and it was felt that there was a good chance that it would survive 50 psi.

The steel building was a steel replication of the concrete building. That is, at full scale an alternative framing system for an equivalent steel structure was formulated using the same floor/beam/girder/column geometric layout as the concrete building. The construction of a small steel building, however, was a little more difficult, and some alternative decisions had to be made. That is, one cannot merely order a fifth-scale wide flange section. Because material availability and relative ease of analysis, it was decided to use square and rectangular tubing that gives approximately the fifth-scale strength and stiffness. Since we were building a small building and not a model, it was felt that it really mattered little whether the section looked the same as in a full scale building, if eventually the behavior of a small building constructed of tubing could be predicted. It is felt that little difficulty should be encountered in computing and predicting the behavior of a large building using wide flange sections.

The design drawings for both structures are presented in Appendix A. The buildings were constructed at the SSI yard in Redwood City, CA and transported by flat-bed truck to the test site. Photographs of the buildings prior to shipment and being installed in the field are presented in Figures 3-3 through 3-6. It will be noted that the buildings were constructed in two parts and assembled in the field at the second floor level. In the back wall of the buildings (the side away from the blast) masonry panels were installed as part of the debris study. The remaining three sides were covered with glass.

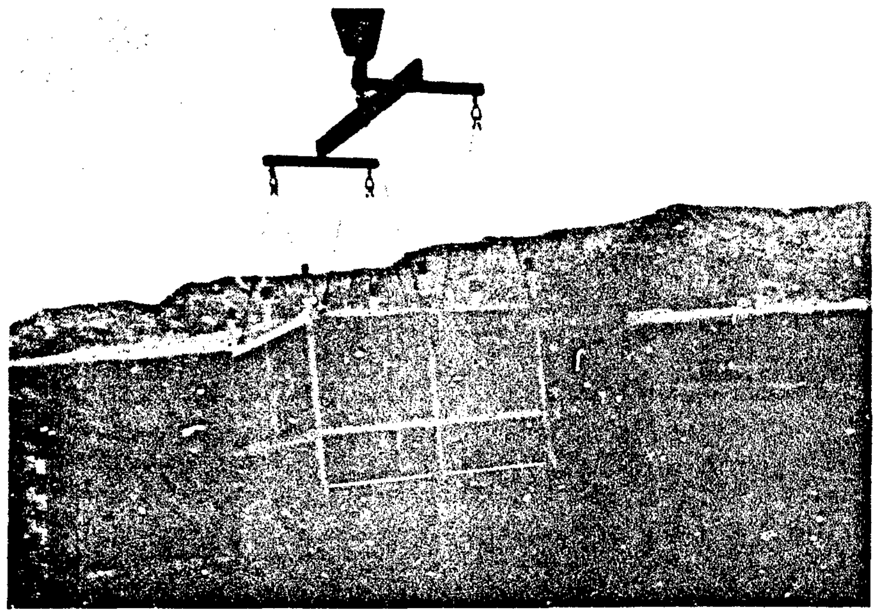


A. Concrete Frame



B. Steel Frame

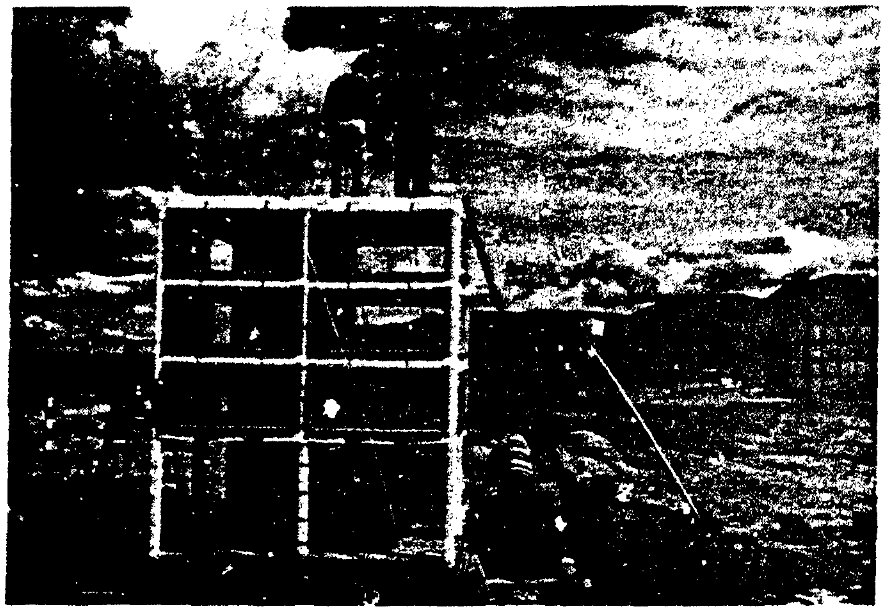
Fig. 3-3. Concrete and Steel Frame Buildings at Construction Site.



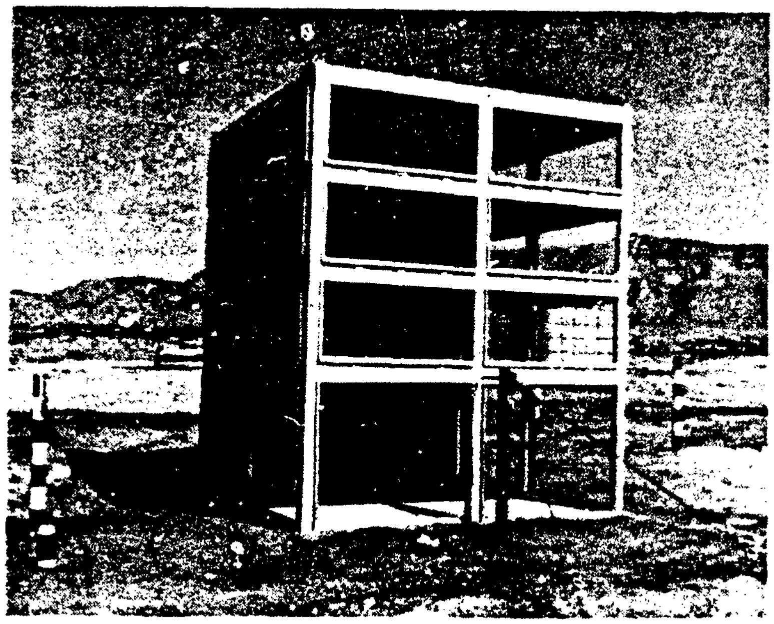
A. Placing Basement and First Story of Steel Frame Building

B. Setting Upper Stories of Concrete Frame Building

Fig. 3-4. Installation of Buildings at Test Site.

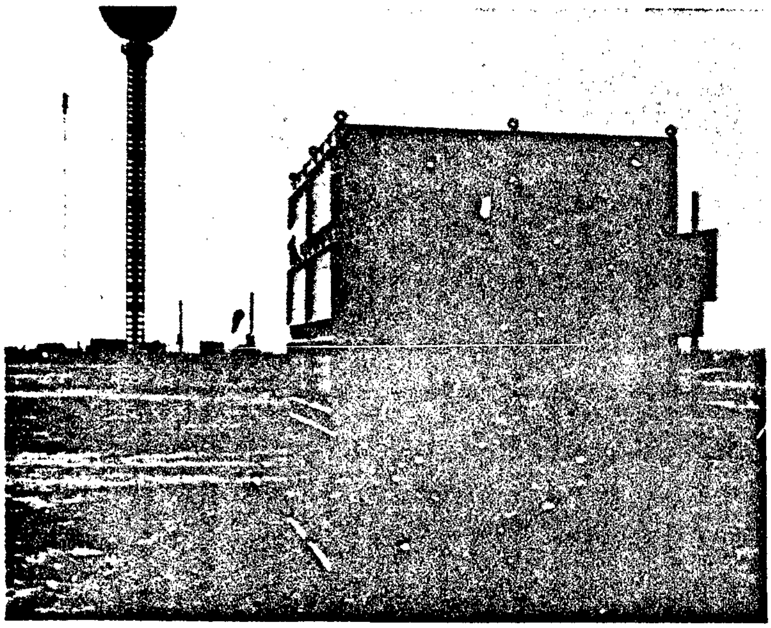


A. Completing Concrete Frame Building

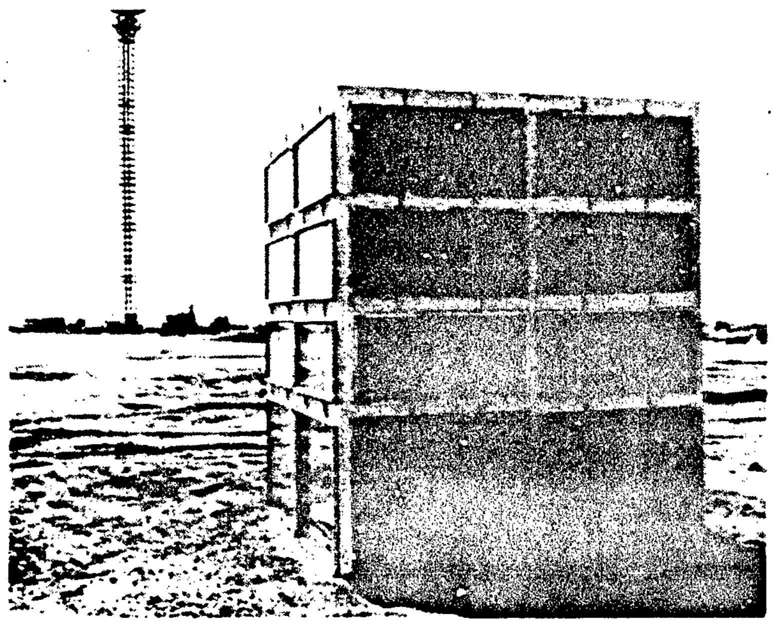


B. Completed Steel Frame From Blast Side

Fig. 3-5. Completion of Concrete and Steel Frame Buildings.



A. Steel Frame



B. Concrete Frame

Fig. 3-6. Views of Completed Buildings Looking Toward Ground Zero.

INSTRUMENTATION

The instrumentation for these experiments was supplied by WES and BRL and consisted of: a free field pressure gauge; pressure and displacement gauges on the front of each structure and a pressure gauge in the first floor of each structure. The primary data source was planned to be high-speed film coverage from three cameras supplied by WSMR/DRI. As will be discussed in more detail in the conclusions section, very little usable film coverage was obtained.

TEST DATA, DISCUSSION, AND CONCLUSIONS

The data from the BRL free field pressure gauge are presented in Figure 3-7. It will be noted that the overpressure was well above the predicted 50 psi and was probably closer to 70 psi. This is confirmed by the WES pressure gauge data from the faces of the buildings shown in Figures 3-8 and 3-9. Calculated side-on overpressures from these data are 74 psi on the steel building and 60 psi on the concrete building.

The steel building (Experiment 4140) was extensively damaged by the blast, as shown in Figures 3-10 and 3-11. The first story columns formed yield hinges at the ground level and at the second story floor line (see Figures 3-10, 3-12, 3-13 for Column line 1 and Figures 3-14 and 3-15 for Column Line 3). The second, third, and fourth stories appear to be relatively intact and square (i.e., they underwent rigid body translation/rotation). The center frame lost all but two of its girders (the first floor girders, which were shored). The center frame, unlike the exterior frames, formed yield hinges at the level of the basement foundation bolts, and rotated without much deformation about the yield hinges at the foundation level (see Figures 3-11 and 3-16). The frame closest to the camera (Column Line 3) translated over 38 inches at the second floor line and translated 49½ inches at the roof line. The second, third, and fourth stories on this particular frame appear to be intact and not to have deformed much, i.e., the frame translated/rotated from its original position without undergoing joint/member deformation. The frame farthest away from the camera (Column line 1) translated 29 inches from its original position at the second

floor line, 50 inches at the third floor line, 57 inches at the fourth floor line and a full 63 inches at the roof line. All of the aforementioned displacements were measured on the front columns (the columns closest to ground zero) and were measured relative to the top of the column at the first floor line.

The steel beams that interconnect the steel frames were in most instances gone after the shot. All of the steel beams along the third floor, fourth floor, and roof are gone. At the second floor level all but one or two of the beams still remain; several of the beams that remain have severed welds at their ends. At the first floor line, many of the beams between column lines 1 and 2 remain, but are badly deformed at the shoring location that originally existed below. It should be noted that in the basement there were several instances where shoring punched through the concrete floor. However, in most instances the basement was a shambles with broken shores, twisted beams, and portions of the concrete first floor. The concrete second, third, and fourth floors and the roof all separated from the structure and were found down range.

Located adjacent to the steel building was the concrete building (Experiment 4145). The concrete building separated at the column splice between the first and second floor lines above the lower yield hinge, see Figure 3-17. The columns, beams, girders and many of the floor slabs for the second, third, and fourth floors are pancaked about 15 feet down range from their original position as shown in Figure 3-18. In the basement a couple of intact shores remain, and there are indications that quite a number of shores punched through the first floor slab, shown in Figure 3-19. A couple of the steel tubular sections, which attach the concrete building to the foundation, were uncovered and there appears to be an indication that these have either shifted or moved from their original position. The basement shear walls in this building are intact and suffered no serious cracking, Figure 3-20. The debris data from both experiments are presented in Appendix B.

In general, both the concrete and steel buildings behaved as predicted. That is, the major deformation occurred at the first (soft) story, with the upper portion of the building acting as a rigid body, as illustrated in Figure 3-2. The one significant difference between the two was the lower ductility of the concrete frame allowed

separation (tension) at the column splices, and the rigid body motion of the upper stories was much greater (15 ft). It also should be noted that these were geometric models not scale models, and no attempt was made to scale the mass; hence, these small buildings were undermassed by a factor of 125. This "mass" effect would greatly reduce the actual "rigid body" motion observed in the test.

Probably the most interesting conclusion to come out of these tests was the fact that they confirmed that it is possible to gain valuable structural failure information using model buildings. This is a very promising approach to study debris translation, building collapse, and other parameters in an urban complex by using a group of these buildings during the next high explosive test.

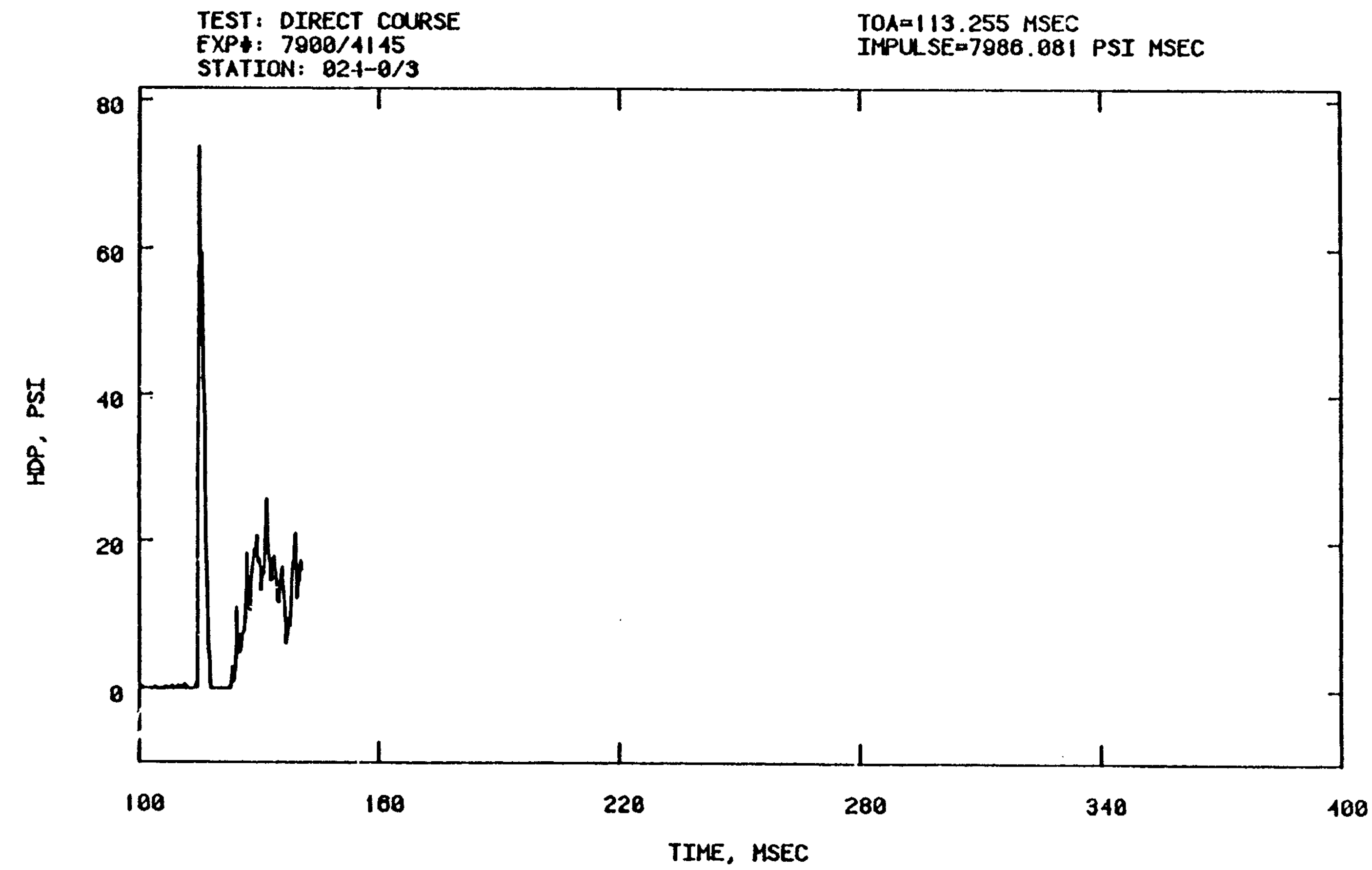


Fig. 3-7. Free Field Pressure Gauge Data From BRL.

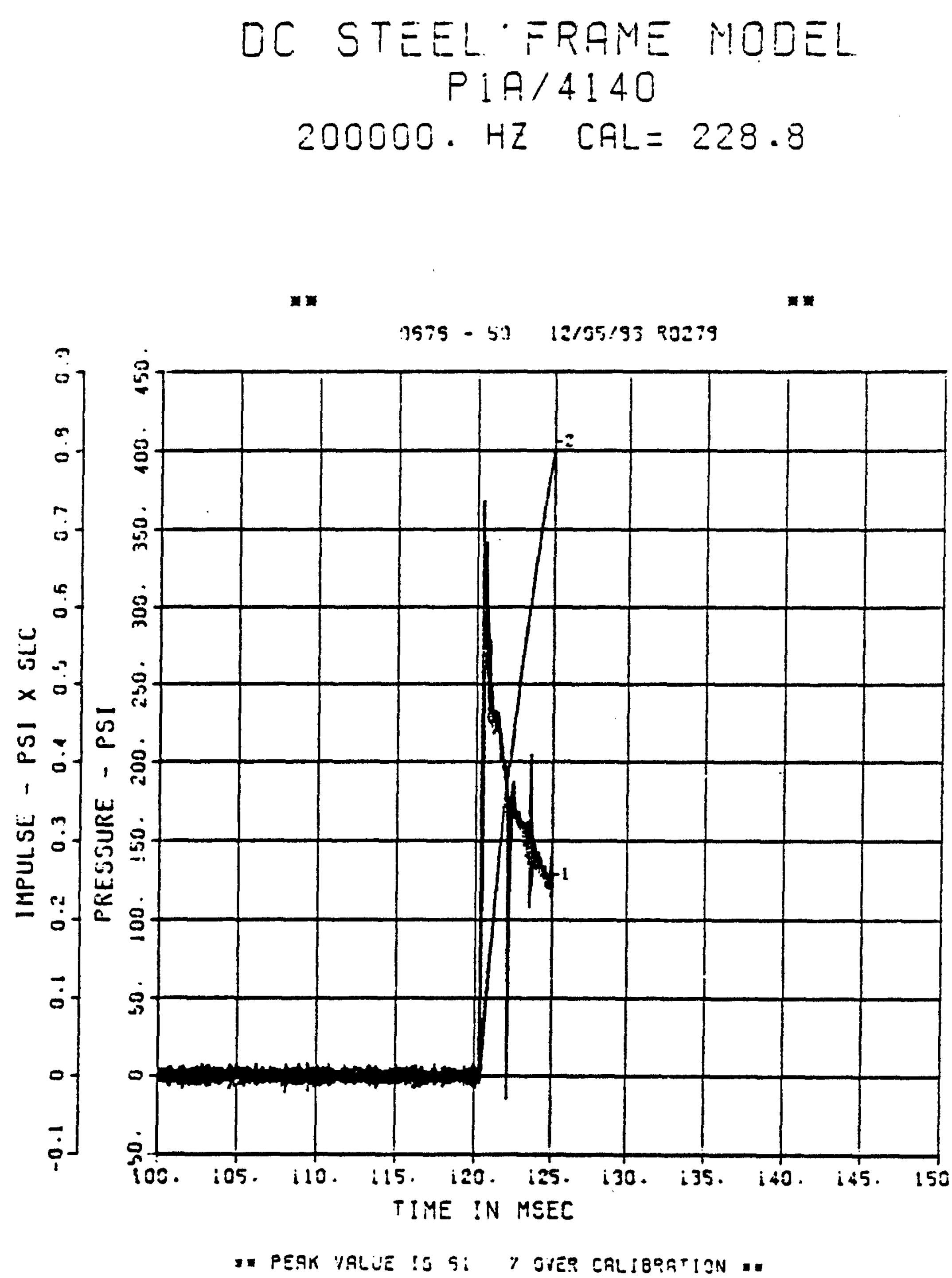


Fig. 3-8. WES Pressure Gauge Data for Steel Building.

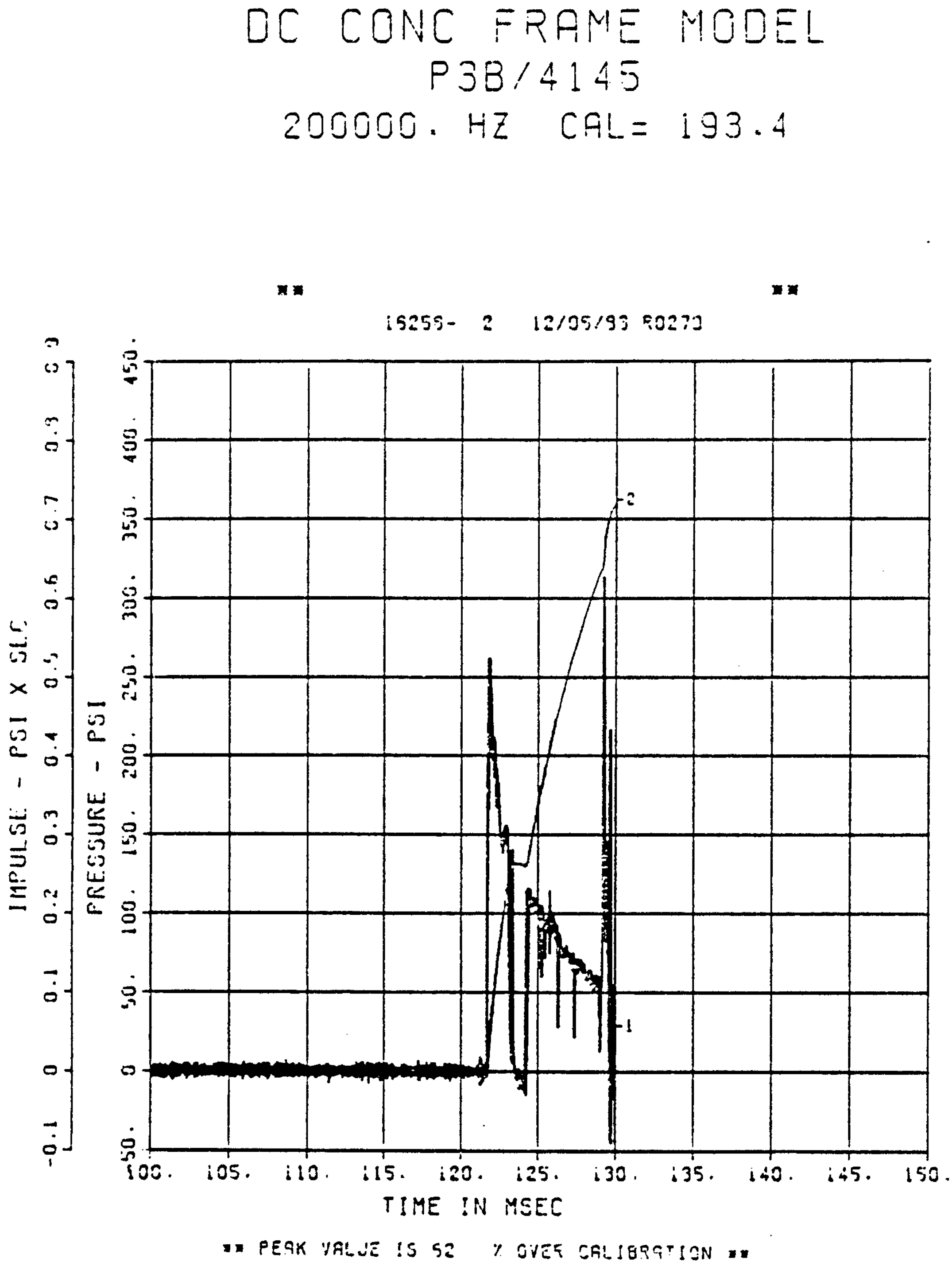


Fig. 3-9. WES Pressure Gauge Data for Concrete Building.

A

B

Fig. 3-10. Posttest Photographs of Steel Frame Building, Experiment 4140.

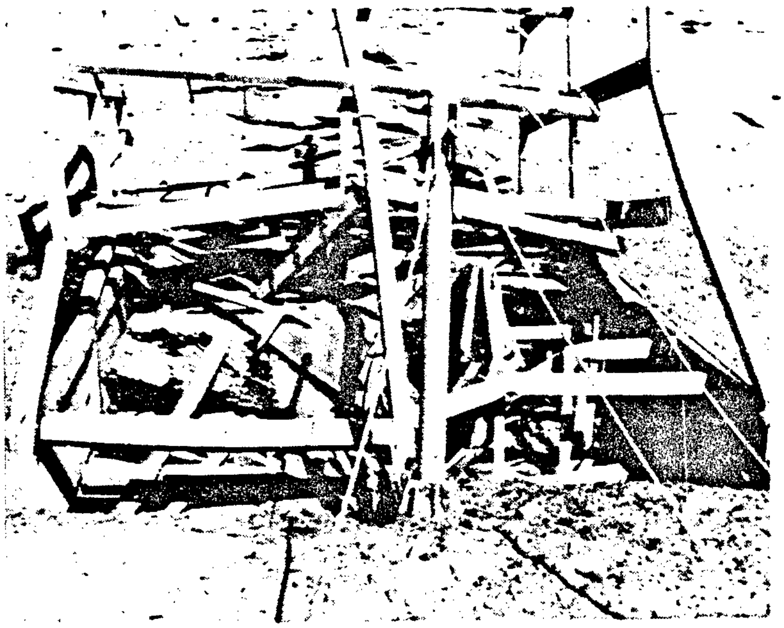


Fig. 3-11. Posttest Photograph of Steel Frame Building, Experiment 4140.

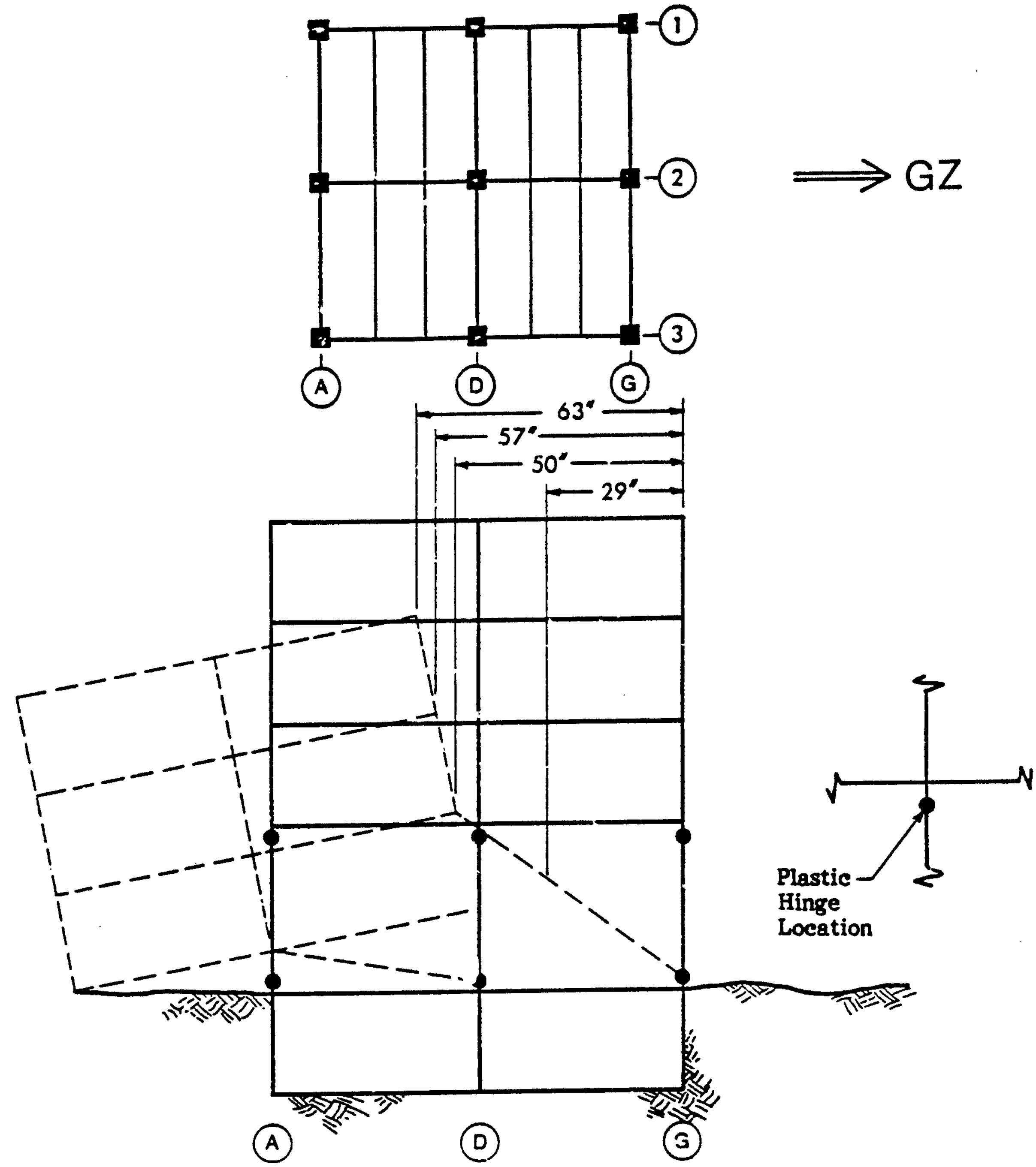
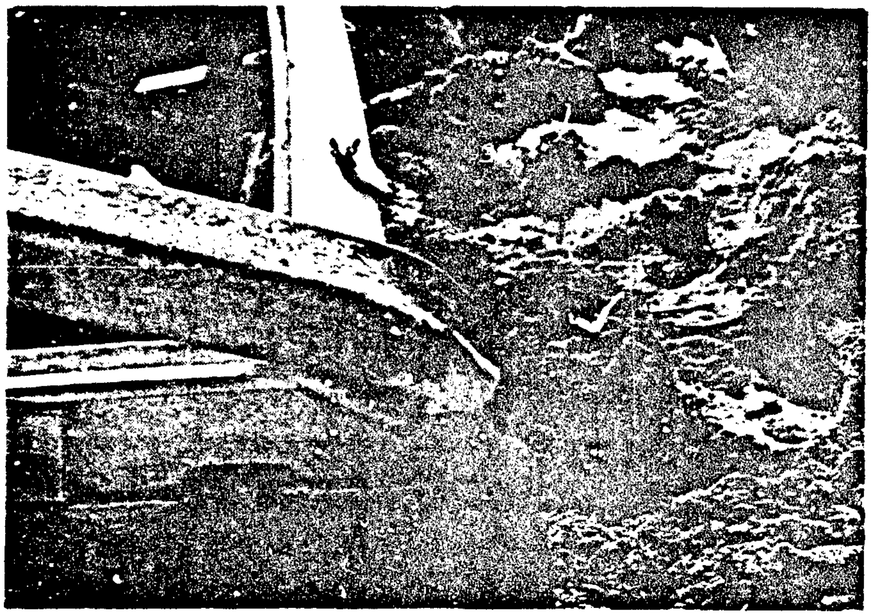


Figure 3-12. Final Deformed Position of Steel Frame Along Column Line (1).



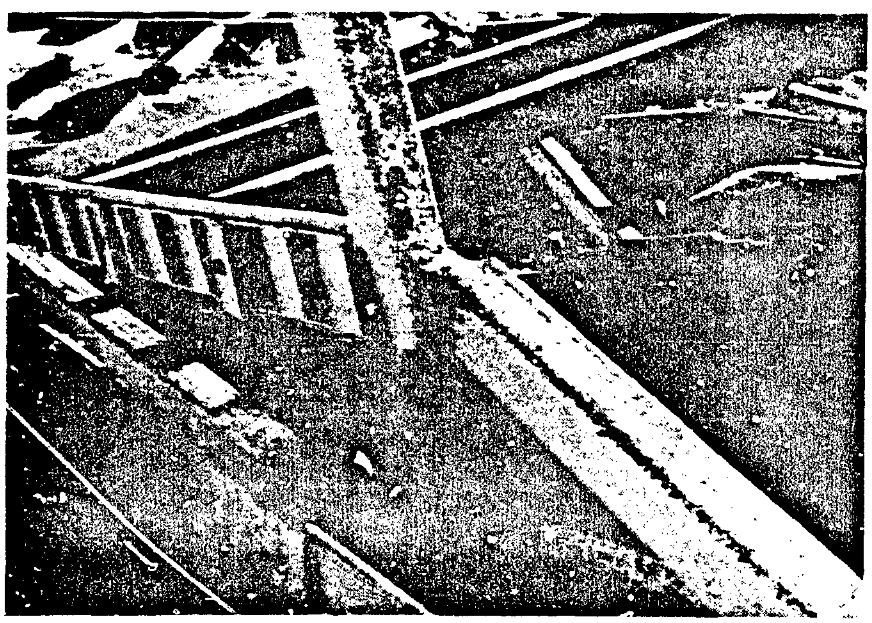


Fig. 3-13. Posttest Photographs of Column Line 1 of the Steel Frame Building, Experiment 4140.

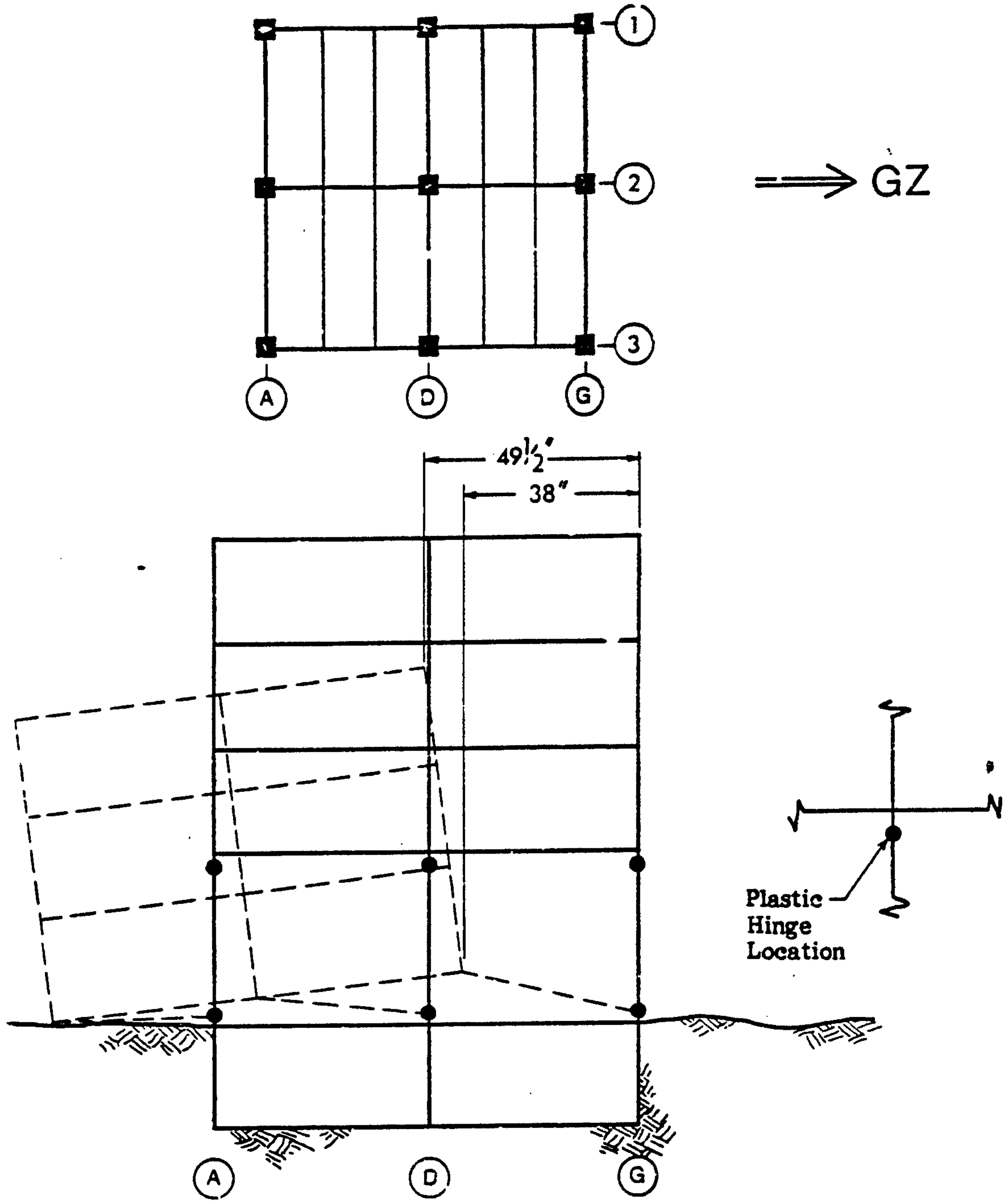


Figure 3-14. Final Deformed Position of Steel Frame Along Column Line (3).

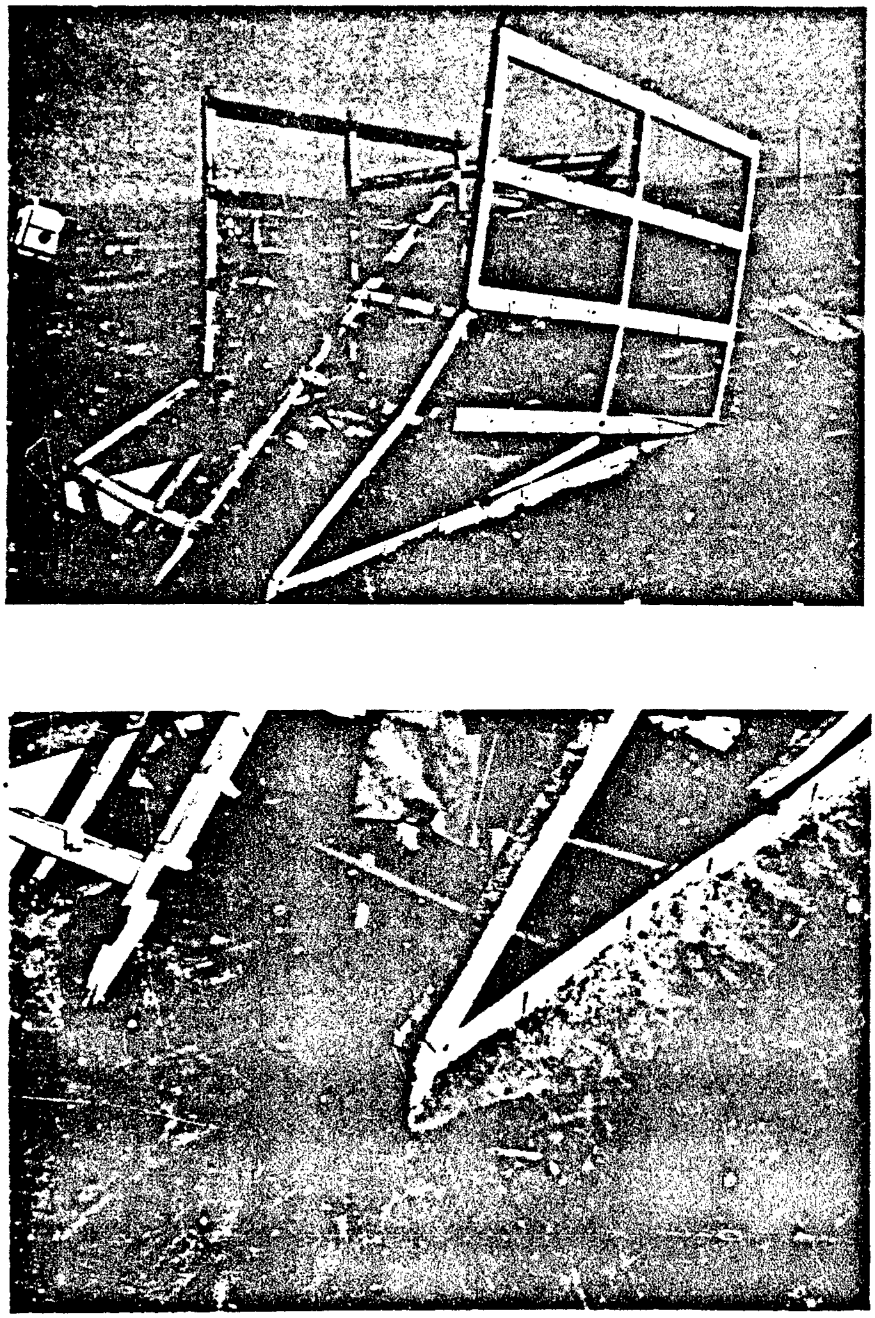


Fig. 3-15. Posttest Photographs of Column Line (3) of the Steel Frame Building, Experiment 4140.

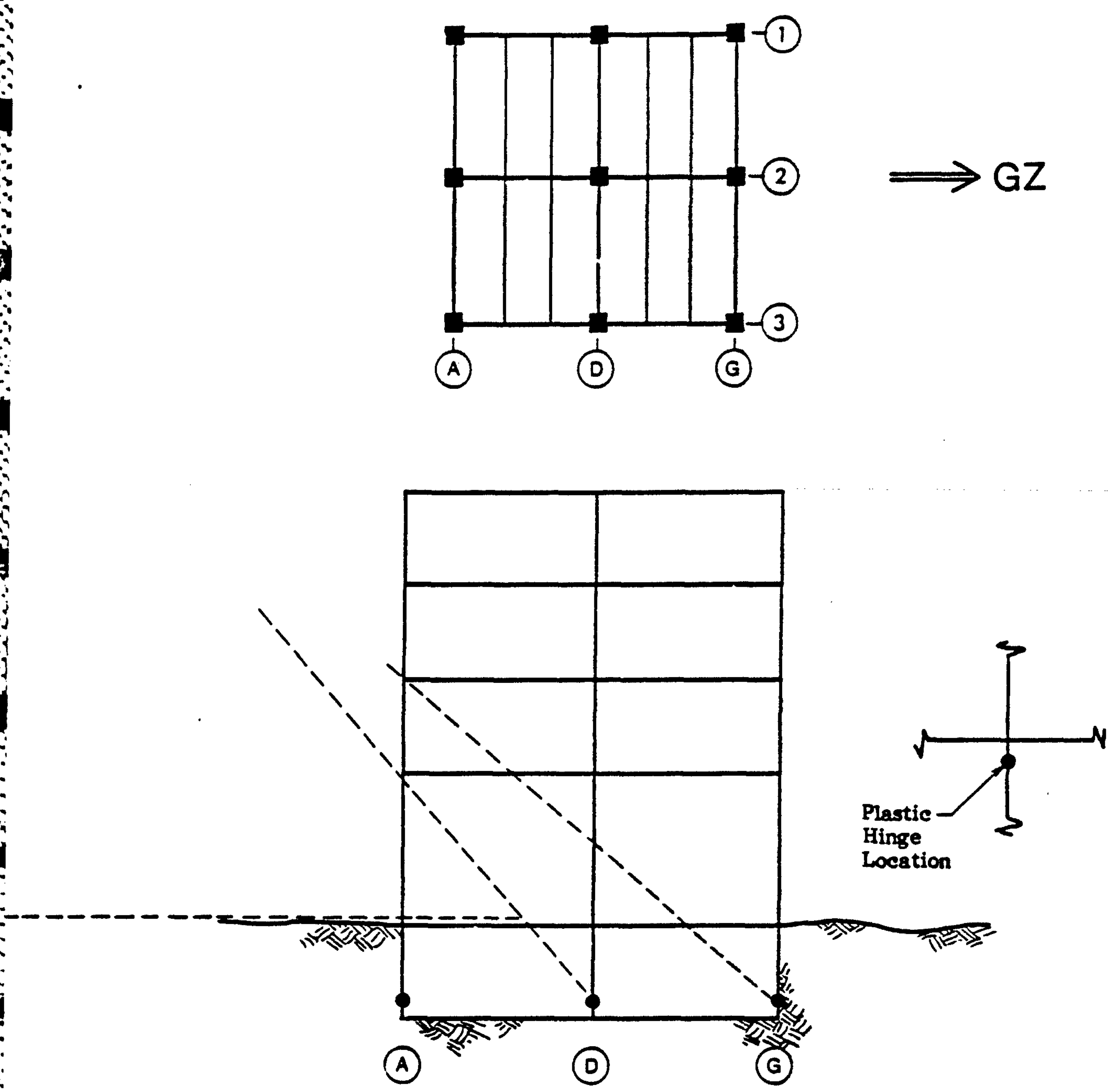


Figure 3-16. Final Deformed Position of Steel Frame Along Column Line (2).
(Note: No girders remain attached to frame No. 2.)

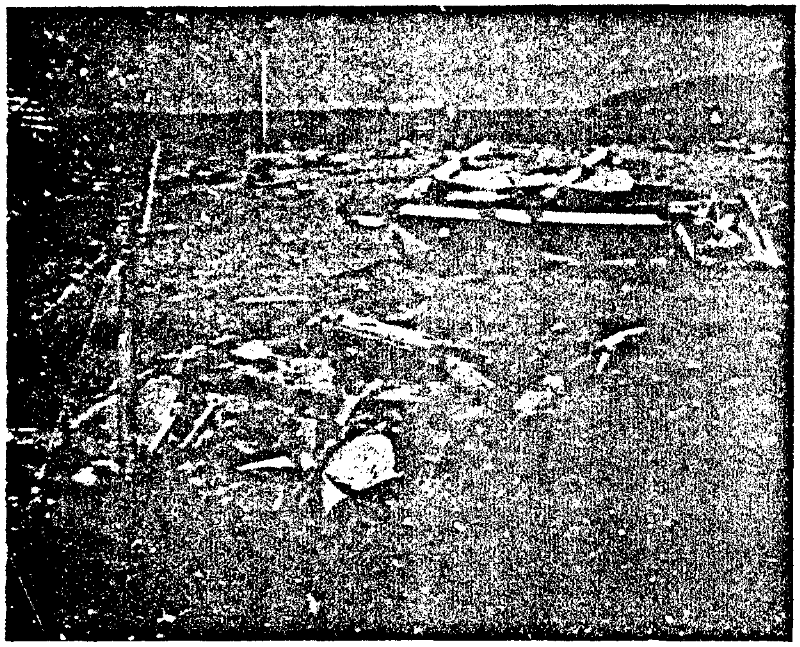


Fig. 3-17. Posttest Photographs of Concrete Building, Experiment 4145.

Fig. 3-18. Posttest Photograph of Concrete Building, Experiment 4145.

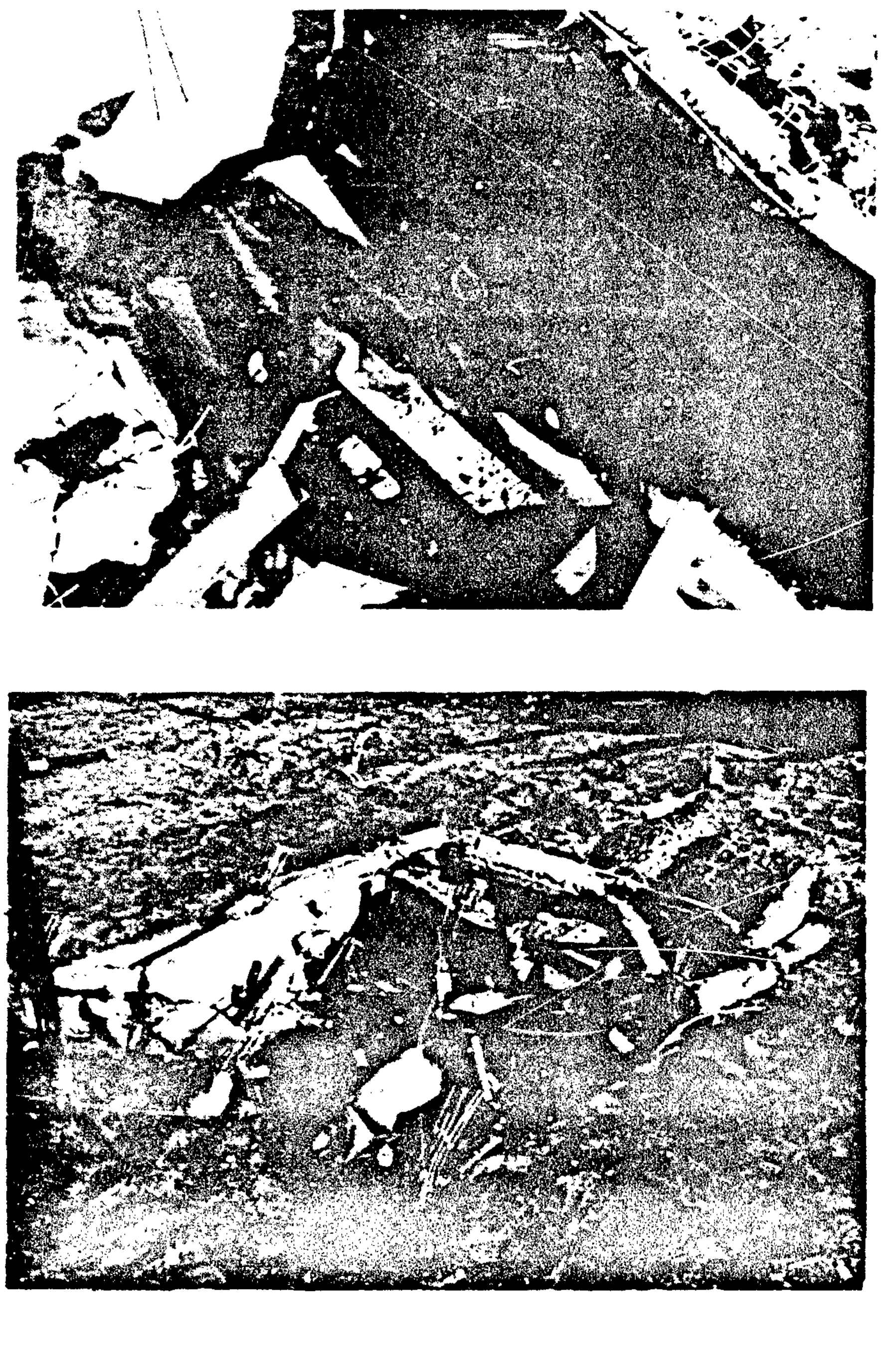


Fig. 3-19. Basement of Concrete Building, Experiment 4145.

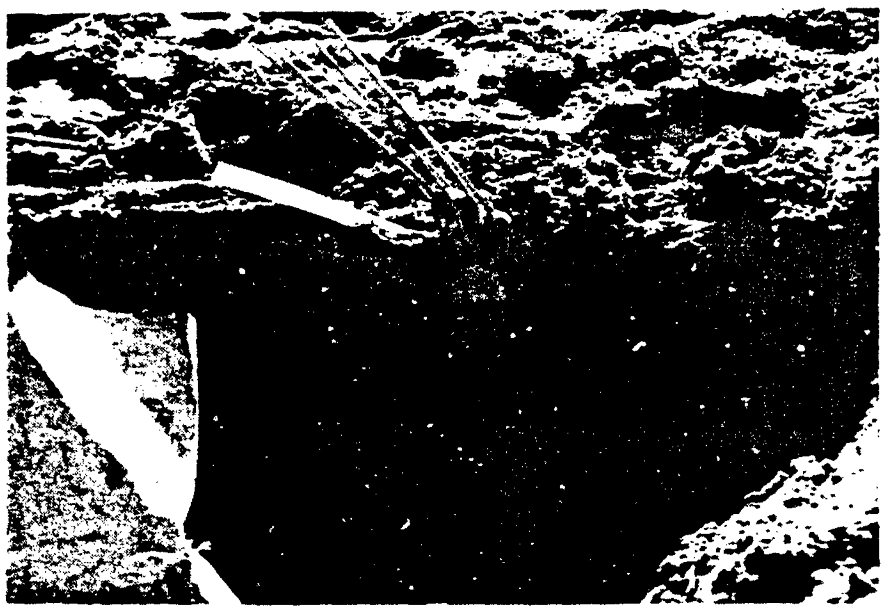


Fig. 3-20. Basement Shear Walls of Concrete Building, Experiment 4145.

Section 4
MODEL BASEMENT WALL EXPERIMENTS
DNA Nos. 4150 and 4160

INTRODUCTION

One important area, with regard to the use of upgraded existing basements as key worker shelters, is the response of the basement walls to the air blast loading of the soil surrounding the structure. Very little is known about the soil/structure interaction between walls and the existing backfill and also the effect of the soil that will be added for radiation protection. During the MILL RACE event, full scale walls were tested in the 40 psi shelter. It had been predicted that some of these walls would fail but, aside from two that developed small cracks, all survived. For a description of these tests refer to Ref. 1.

Subsequent to the MILL RACE event, SSI conducted an extensive small scale shock tube test program on basement walls. These experimental tests were conducted in the SSI 12-inch shock tube on one-twentieth scale models of below grade walls to provide data on their vulnerability to blast waves. The study was initiated to determine those parameters that have the most effect on shelter vulnerability. The short term objective was to identify which parameter or parameters have the major effect. The long term objective (requiring many more tests and quite beyond the scope of that program) would be directed toward the development of a quantitative basis for supplying better design information to the task of reducing structural vulnerability at minimum expenditure of resources. The tests conducted at DIRECT COURSE were a step in that direction.

BACKGROUND

Before presenting a description of the DIRECT COURSE model basement wall experiments a review of the shock tube tests is in order. Figure 4-1 summarizes the

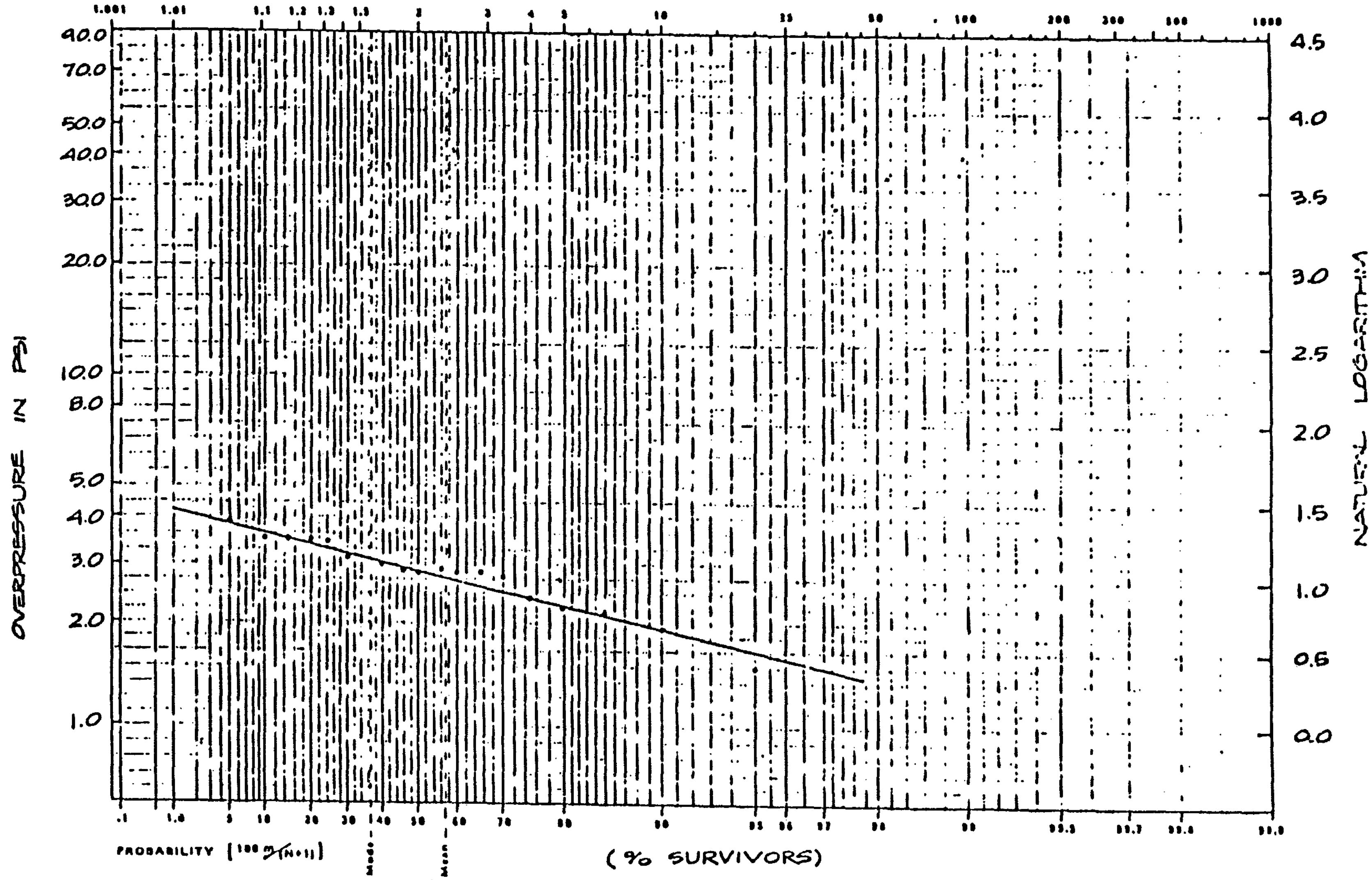


Fig. 4-1. Probability Distribution Curve Governing Survival (Failure) of Walls Uniformly Loaded.

inherent variability in failure strength of a set of test walls when they were simply supported on two edges, and failure was in bending. Though these reference tests were conducted as out-of-plane loading at the third points, they have been converted to an equivalent uniform loading that will cause failure in bending. (For loading at the third points, the maximum bending moment occurs over the entire third of the wall. Failure in bending can be related to extreme fiber stress, or modulus of rupture, and from that to a uniform loading over the surface that would produce the same extreme fiber stress as the loading at the third points that caused failure.)

With inherent failure probability of the set of test walls determined, tests were subsequently conducted on walls from the same batch, but in the configuration shown in Figure 4-2. The entire below-grade assembly was mounted in a box equipped with a transparent side wall so that, as the static overpressure on the surface was gradually increased, wall cracking and collapse could be observed. Table 4-1 contains a typical set of data, and Figure 4-3 is a plot of cracking and collapse probabilities for static loading on the surface. Comparison of Figure 4-3 with Figure 4-1 shows that, for whatever reasons, the 95% probability of surviving a uniform loading on the surface (which will not result in a uniform loading on the below-grade wall) for the geometry of Figure 4-2 is 13 times the probability of surviving a uniform out-of-plane load. This difference increases to 23 times at the 50% probability of survival, and is different at each percentile because the two lines representing failure probability are not parallel. (They would be parallel only if the same flaw variation applied to both configurations.)

The existence of this difference is very important design information - but it will not be truly valuable until it is clear just what factors are principally responsible. Information exists (Refs. 6 to 9) that suggests coefficients of earth pressure at rest (the equivalent of a Poisson ratio, in soils) for the dry sand used as backfill in these experiments should range from 0.25 to 0.65. Such information implies that the loading configuration can account for only 1/0.65 to 1/0.25 (i.e., 1.5 to 4 times) out of the 13 times difference observed at the 95 percentile survival loading (or, just a fraction of the 23 times difference noted at the 50 percentile survival loading). Further, studies of columns of compressible materials in rigid walled containers (e.g., grain silos) indicate that load falls off rapidly with distance

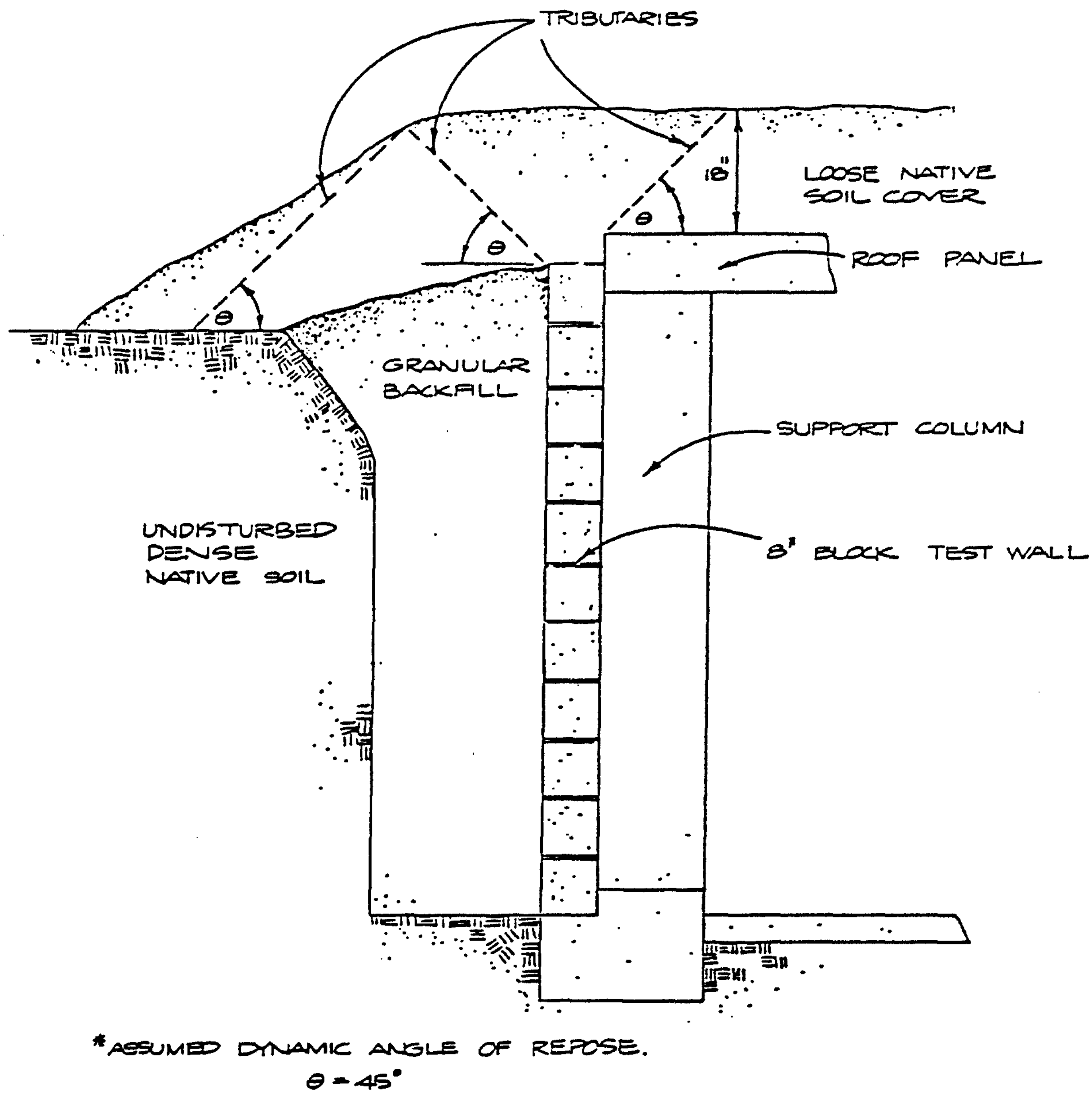


Fig. 4-2. Test Configuration for Below-Grade Scale Model Study (1/20th scale).

TABLE 4-1

STATIC BELOW-GRADE WALL TESTS

Test Number	Cracked	Collapsed	No Collapse*
	(overpressure in psi)		
1	31	--	51
2	35	--	55
3	17	31	--
4	12	--	61
5	21	--	61
6	15	--	60

* Experiment maximum

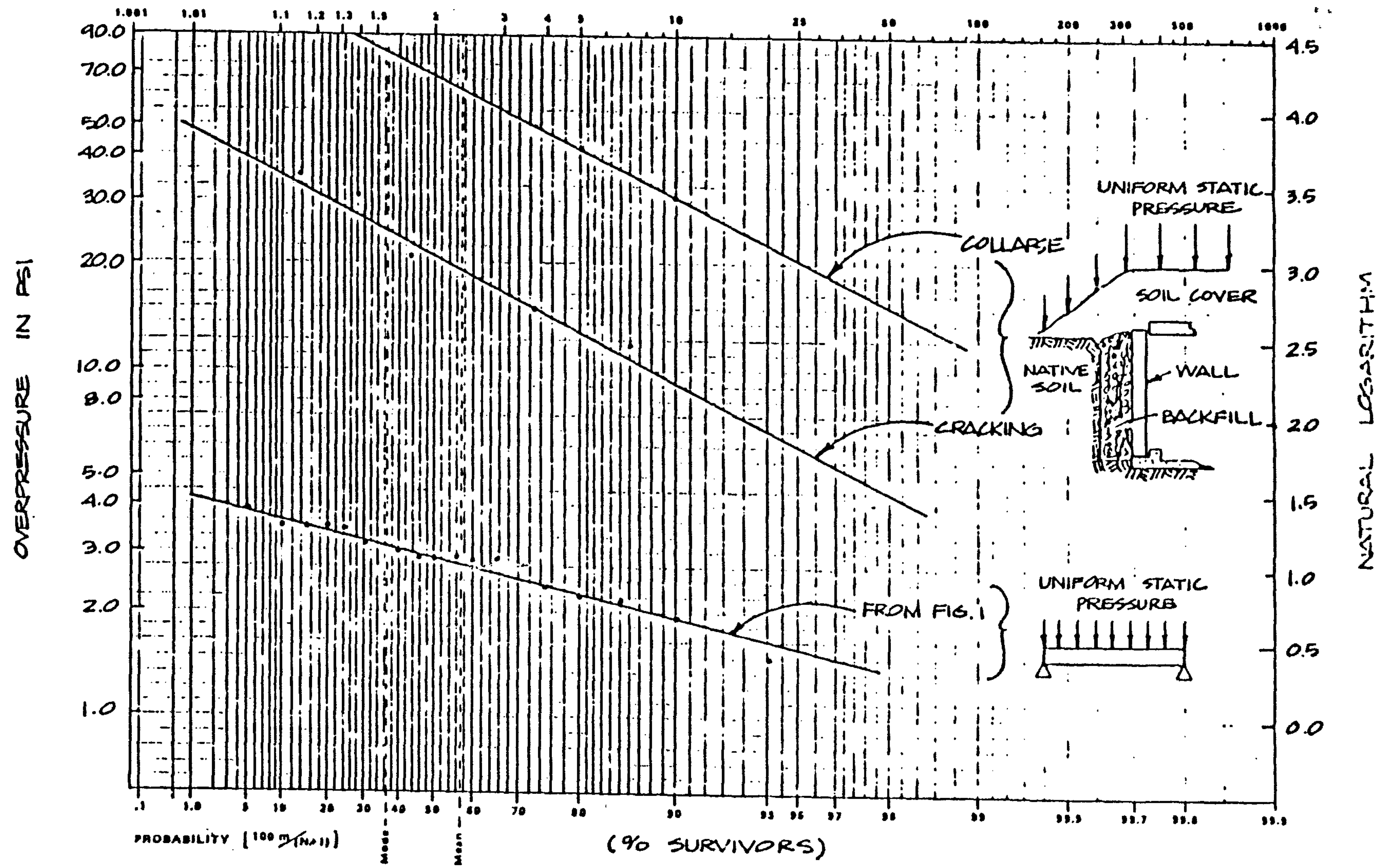


Fig. 4-3. Probability Distribution Curves Governing Survival (Failure) of Below-Grade Walls versus Uniform Loading.

down a column, because of side wall friction, so that in a distance equal to three or four container widths, there ceases to be a transference of load through the column even if very significant additional load is applied to the material ahead. This circumstance reduces the load on the below grade wall by changing the distribution (decreasing exponentially with depth). Refs. 10 and 11, however, suggest that sharp-fronted dynamic loading (such as that from a propagating airblast wave) can have the effect of increasing the applied loads because of stress wave reflections at boundaries of dissimilar materials (e.g., the soil/wall interface). Very important questions, therefore, are the effects of passive arching in the walls, active arching in the backfill, transfer of load to the rigid walls adjacent to compressible backfill, dynamic versus static effects, and the size of weapon (hence, loading pulse).

Pulse duration becomes particularly important when loading on a member falls off to a fraction of the peak value before the member has reached maximum deflection. In such a case, the member may never reach failure deflection even though the peak load would have been sufficient to ensure failure, had it remained constant. SSI evaluated all these effects to determine which might be the most important.

Subsequent to the static loading tests (which enabled the entire failure probability distribution curve to be traced), dynamic tests were conducted (using the same geometry) in which nominal 40 psi surface loadings (at 1/20th scale) were simulated for both nominal 1 kt and nominal 1 Mt weapons.

In Figure 4-4, the upper two curves from Figure 4-3 have been reproduced (together with a dashed line, drawn to represent the expected failure probability for dynamic, sharp-fronted loadings, when the applicable reflection factor is 2.0) so that the results of the dynamic tests can be plotted and compared. For the 1/20th scale "1 kt" simulation, the nine tests showed a peak overpressure of 42 $\pm$ 1 psi with three walls collapsing and the remainder cracking (plotted as the upper square). For the 1/20th scale 1 Mt simulation, the results from the ten walls tested showed a peak overpressure of 36.5 $\pm$ 2 psi with three walls collapsing and the remainder cracking (plotted as the lower square). Both these probabilities fall between the static and dynamic curves representing probability of failure (collapse), with the 1 Mt

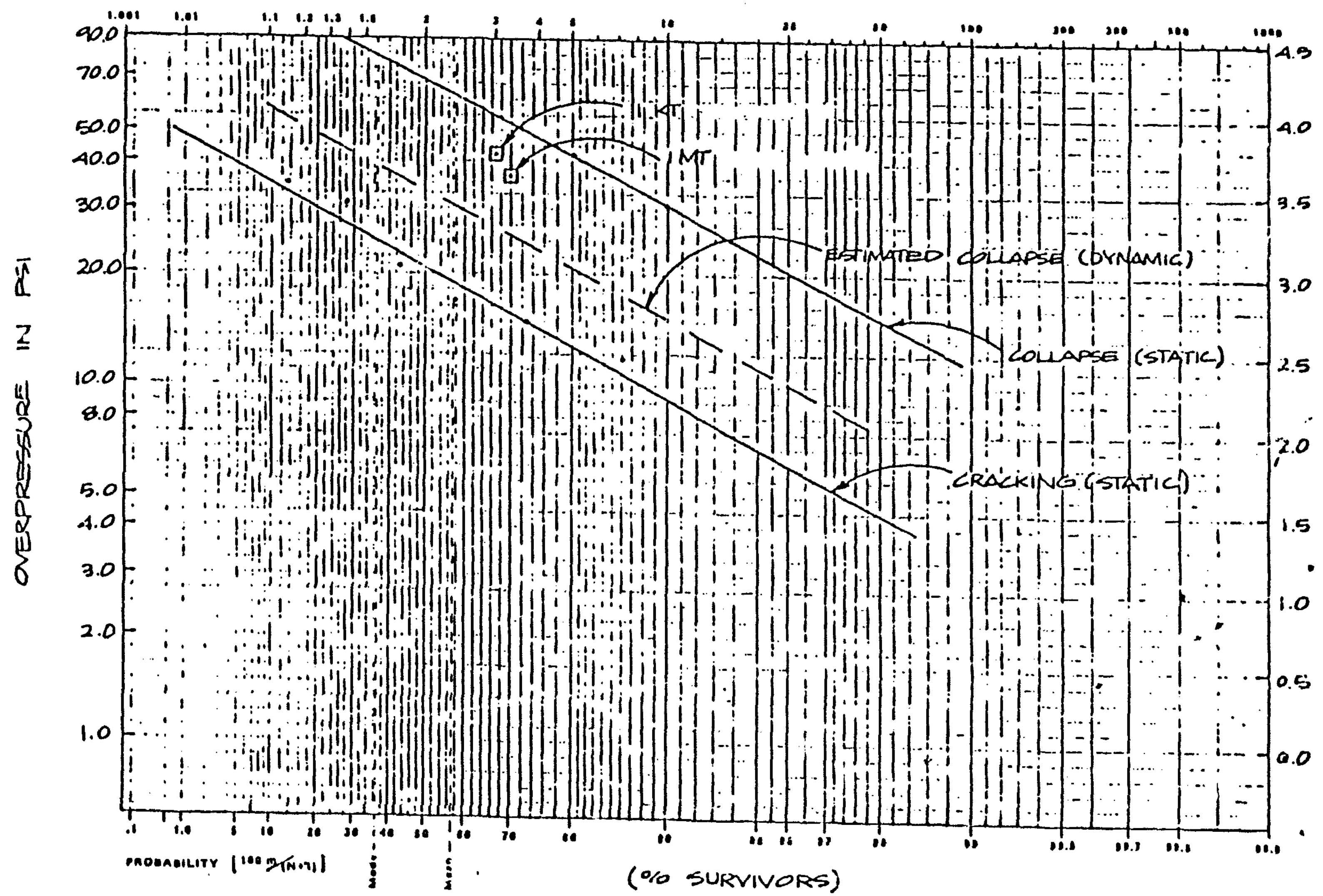


Fig. 4-4. Probability Distribution Curves and Data for Survival (Failure) of Below-Grade Walls.

simulation a little worse, from the point of view of the shelter survival, than the 1 kt simulation. The observed difference is not enough to qualify as a major factor; however, it is a real difference that should be studied with regard to below-grade shelters.

To see if it could be trench width, the 1 Mt simulation was repeated with the trench width increased by a factor of 2.3 so that the width was now 1.4 times the depth (versus 0.6 times for the previous tests). Seven tests were conducted with peak overpressures of 31 $\pm$ 2; and one wall was observed to collapse, five cracked, and one survived. When these data (12.5% survival without cracking - the solid diamond, and 87.5% survival without collapsing - the open diamond) are plotted with the data of Figure 4-4 (see Figure 4-5); each agrees with the corresponding probability distribution curve for static cracking and static collapse. Within the experimental limits of error, this outcome also agrees with the other dynamic test data, indicating that the radical change in trench width was not very significant.

The remaining factor evaluated, in the apparent increased strength of the below-grade walls over the referenced loading condition, was passive arching. To preclude passive arching on the walls, a 1/16th-inch layer of styrofoam (reportedly having a compressibility of 20% at 40 psi) was placed on top of the walls, and another series of eight tests was conducted using the 1 Mt simulation and the trench width as in the previous series. In this set of tests, the average peak overpressure was 34.4 $\pm$ 3 psi; five of the walls collapsed, while the remaining three walls cracked. This 32.5% probability of surviving collapse (the open circle on Figure 4-5) was radically different from all the other data, showing passive arching to be a major factor affecting the apparent strength of below-grade walls.

A preliminary additional set of tests was conducted using the same configuration, but with loading conditions designed to simulate a 14 psi incident overpressure on an above-grade structure that will survive 20 ms (i.e., 1 ms scaled duration) before collapsing. This would be expected to correspond, roughly, to the survival time of lightweight panels in a steel frame building, and would produce a nominal peak reflected overpressure of 40 psi for 20 ms (1 ms scaled) before the structure collapses, and a nominal 14 psi overpressure decaying very slowly

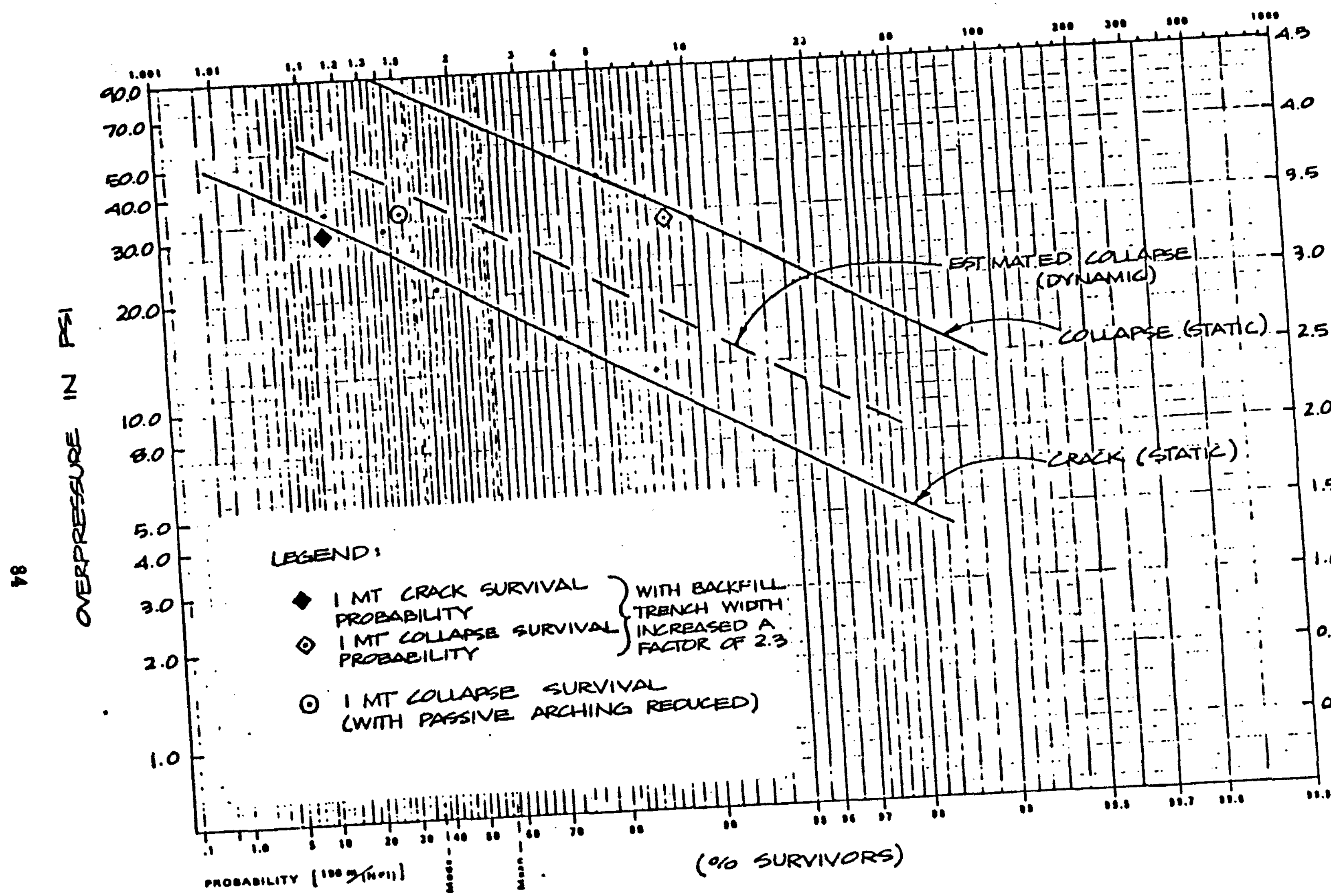


Fig. 4-5. Probability Distribution Curves and Data Showing Minor Role of Active Arching and Major Role of Passive Arching.

thereafter. Seven tests were conducted with the incident overpressure averaging 13.4 $\pm$ 0.3 psi (corresponding to 35.9 psi peak reflected). One of the walls collapsed and the remainder cracked, corresponding to 86% survival. Plotted against 13.4 psi (see the solid circle in Figure 4-6), the result agrees with the previous test series (a line passed through this point and 34.4 psi at 32.5% survival is very nearly parallel to the two referenced probability distribution curves), suggesting that for structures that survive only a matter of milliseconds, the peak reflected overpressure may not last long enough to affect the below-grade walls. Nevertheless, it is prudent to check the sealing.

OBJECTIVE

The primary objectives of the experiments on model basements conducted during the DIRECT COURSE event were to obtain data on a larger scale (approximately 1/5 scale), to investigate the effect of a range of backfill materials, and to assess the importance of reflections off above-grade portions of structures on below-grade response (something not previously examined anywhere insofar as is known).

DESIGN

Test Layout

Eight prefabricated basements approximately 48 inches long, 18 inches wide, and 16 inches deep, each containing three walls, were tested. Six of these basements were installed at the predicted 50 psi range as DNA experiment No. 4150. A photograph of these basements in place is shown in Figure 4-7 and a test layout, indicating the types of backfill used and the location of the ones that had frangible walls, i.e., simulating an aboveground structure, is presented in Figure 4-7B. The two additional basements were installed at the predicted 18 psi range as DNA experiment No. 4160. A photograph of one of these models and a test layout sketch are shown in Figure 4-8.

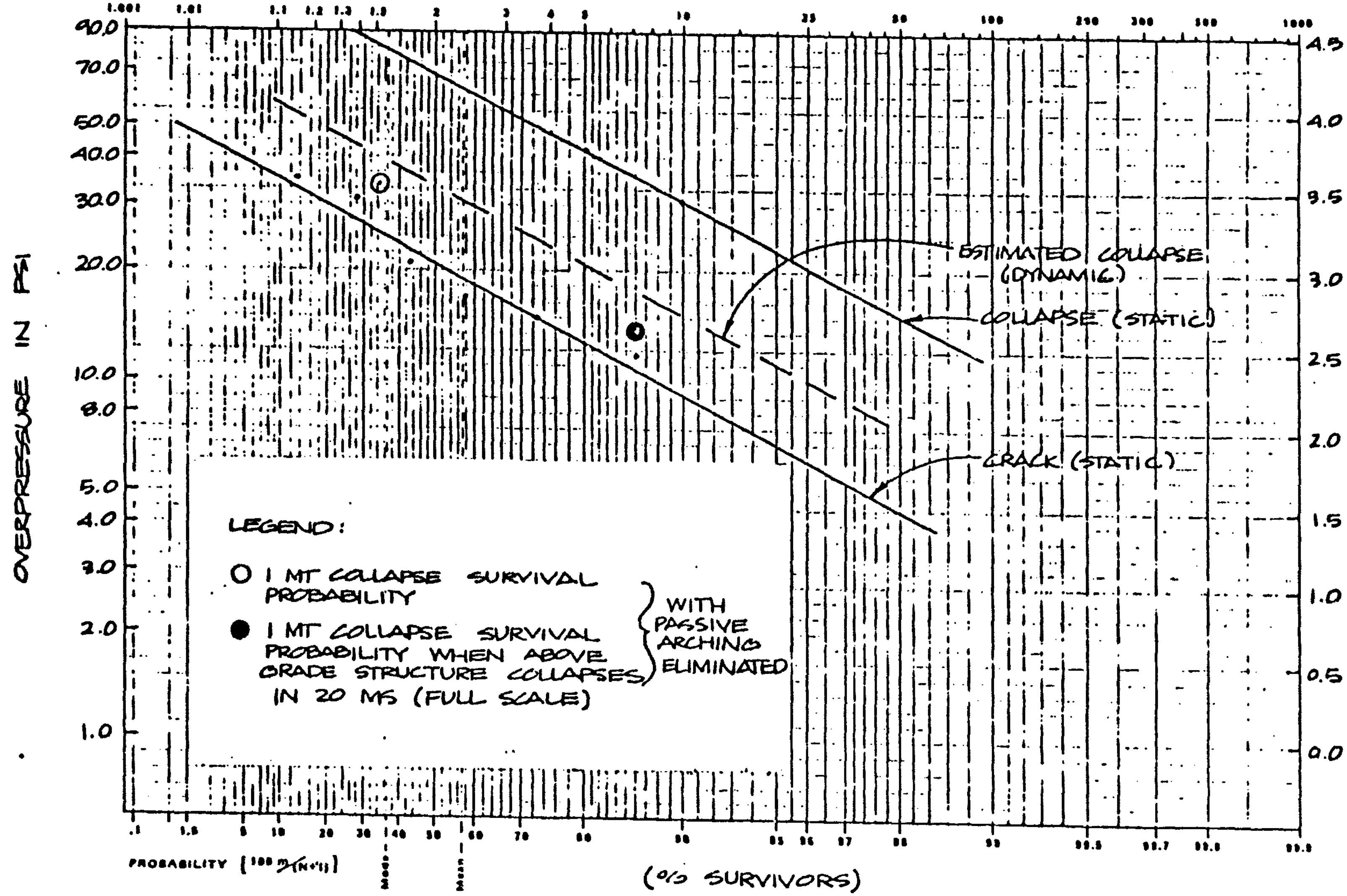


Fig. 4-6. Probability Distribution Curves and Data Showing Initial Assessment of the Effect of Reflection Off an Above-Grade Collapsing Structure on Below-Grade Wall Survival.

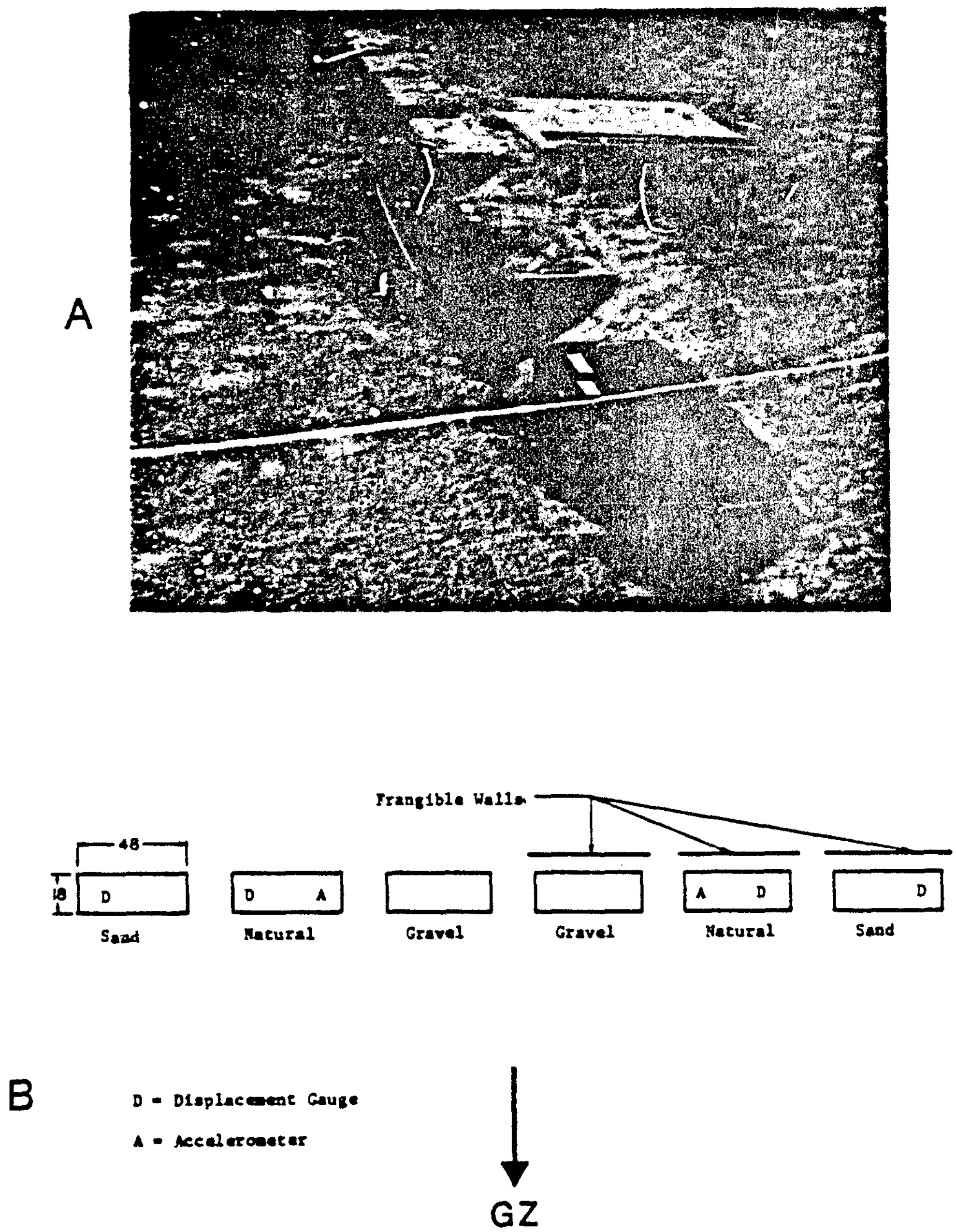


Fig. 4-7. Test Layout for Experiment 4150.

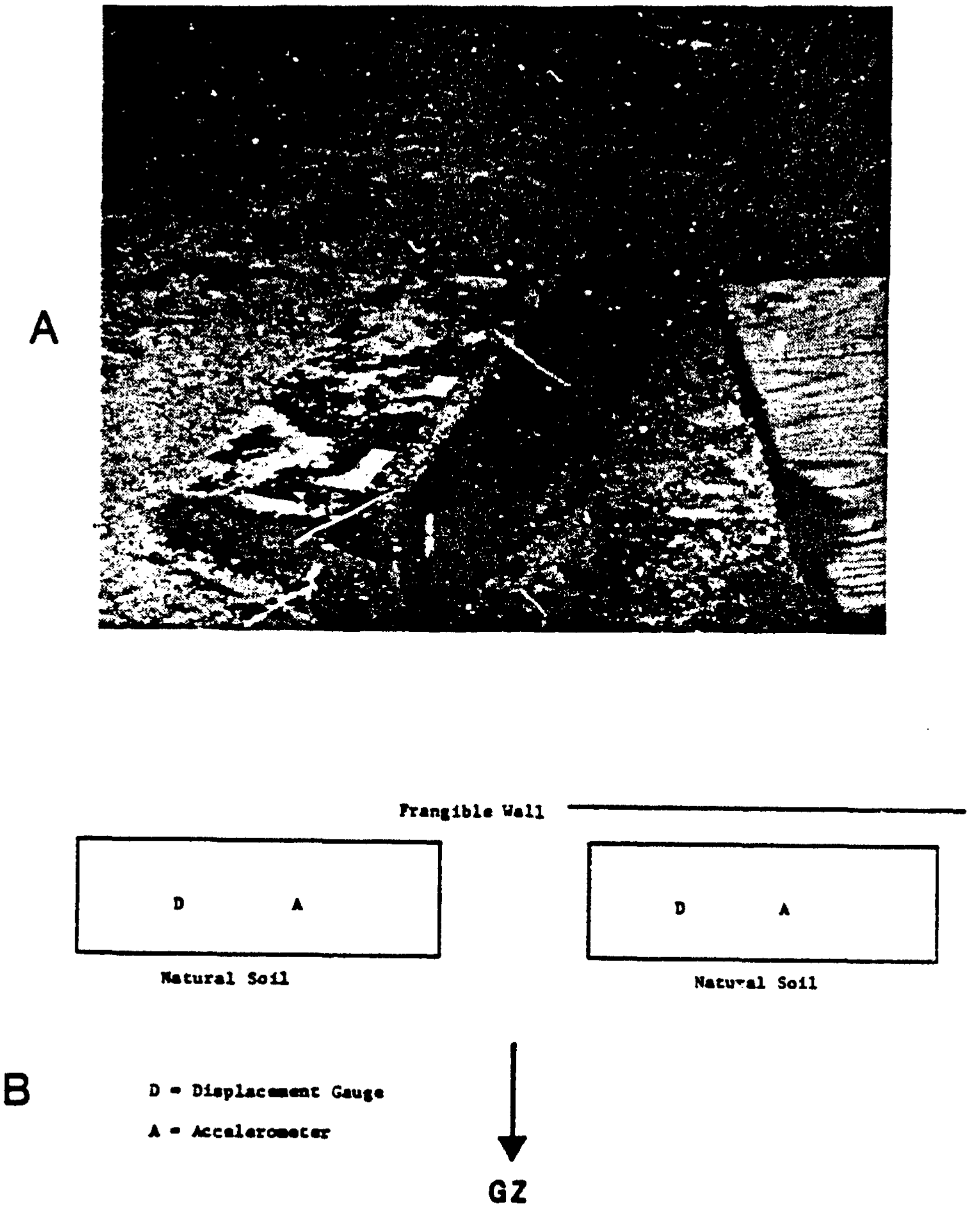


Fig. 4-8. Test Layout for Experiment 4160.

Instrumentation

As noted in Figures 4-7 and 4-8, displacement gauges were installed on four of the test walls at the expected 50 psi level and on two walls at the 18 psi level. Accelerometers were placed on two walls at the 50 psi level and on two walls at the 18 psi level.

TEST DATA, DISCUSSION, AND CONCLUSIONS

Pretest predictions were that the walls would survive in experiments 4150-A (50 psi, sand backfill without above-grade wall) 4150-C (50 psi, gravel backfill without above grade wall) and 4160-A (18 psi, native soil without above-grade wall). The walls in some of the other experiments would crack and in some cases fail.

The estimated overpressures from the BRL north radial were 54.96 at the expected 50 psi range and 19.92 at the expected 18 psi range. Pressures recorded by WES on experment 4195 that was next to the 4150 experiment indicated that the overpressures could have been approximately 80 psi. This would suggest that the overpressures at the 18 psi range were also much higher than expected.

All the walls failed in this experiment, and it is suspected that this was, at least in part, because of much higher than expected overpressures (where the Mach stem formed may also have played a role). Thus, it is not possible to make any conclusions with regard to the survival prediction validity based on this experiment. The displacement gauge and accelerometer data, however, did yield some very useful information. One of the objectives of the experiments was to determine if the above grade portion of the structure, even though it only remains for a few milliseconds, could have an effect on the loading seen by the below-grade basement walls.

A summary of these data follows:

Experiment 4150

4150-A, Sand backfill without above-grade structure

Initial Velocity (first 10 ms) - 22 in./s

4150-C, Gravel backfill without above-grade structure
Initial velocity (first 10 ms) - 24 in./s
Acceleration - 20 g's

4150-E, Native soil backfill with above-grade structure
Acceleration - 45 g's

4150-F, Sand backfill with above-grade structure
Initial velocity (first 10 ms) - 51 in./s

Experiment 4160

4160-A, Native soil backfill without above-grade structure
Initial velocity (first 10 ms) - 6.6 in./s
Acceleration - 10 g's
Maximum velocity - 60 in./s

4160-B, Native soil backfill with above-grade structure
Initial velocity (first 10 ms) - 14 in./s
Acceleration - 18 g's
Maximum velocity - 98 in./s

A review of the above data indicates that in every case the velocities and accelerations were significantly higher for the experiments with above-grade walls than for the corresponding ones without such walls. This was a somewhat different conclusion from that obtained in the shock tube test series and suggests that more work is needed on the effect of above-grade structures on the loading of basement walls with particular attention paid to observing the mode of failure before accurate failure or survival predictions can be made. It also suggests that tests should be run at a range of scale sizes, probably in the shock tunnel.

Section 5
CLOSURE TESTS
DNA NO. 4170

INTRODUCTION

This experiment consisted of the design and testing of six expedient closures. Open-top steel flange boxes buried flush with the ground surface were used to simulate the shelter space to be sealed. Three of the openings were 4 ft X 4 ft and three were 6 ft X 4 ft. All boxes were installed at the expected 50 psi range.

OBJECTIVE

An important aspect in upgrading basement shelters is the use of expedient closures for openings such as stairways, elevator shafts, and ventilation holes. Permanent closures will be suitable for many of these openings because they will not be needed for ingress/egress of the shelter users.

According to Ref. 4 (key worker shelter manual), based on elastic reponse, a steel closure for a 4 ft X 4 ft opening would require 1.25 in. thick steel plate, which would weigh 1,020 lb for a 4 ft X 5 ft piece, sufficient to close a 4 ft X 4 ft hole. To be truly expedient, the weight of the closure materials must be considered. Because protection of permanent closures against blast can be provided by the strength of the closure material combined with the protection and interaction of the soil covering required for radiation protection, common materials that can be moved with relative ease might be used instead. Consequently, this experiment was designed to test six horizontal closures consisting of pieces of timber, sheet steel, and corrugated sheet steel at considerable savings in weight to make the closures implementable by hand. Expectations were that four of the six closures would perform satisfactorily at the expected 50 psi level.

DESIGN

The pre-fabricated buried steel boxes were designed to be stiff enough to withstand the blast and were constructed out of 10 in. X 8.4 lb/ft steel channel walls, 3 in. X 3 in. X 0.25 in. steel angles used as stiffeners on 12 in. centers, and 3/8 in. plate used as bearing surfaces. Figure 5-1 shows an orthogonal section view of a box. Figure 5-2 is a photograph of a box in place, and Figure 5-3 pictures the layout of the boxes with ground zero to the left.

For the closures, the thicknesses of materials were based on diaphragm theory from static loading in a shock tube, the length and width of closures were chosen from common stockage at retail suppliers, and the weight of the closures was considered from the standpoint that the lightest proven closure would be the best.

The closures for the six openings were as follows:

4170A - 13 gauge sheet steel, 0.0938 in. thick, 4 ft X 10 ft, sheet weight = 150 lb.

4170B - 18 gauge sheet steel, 0.0500 in. thick, 4 ft X 10 ft, sheet weight = 80 lb.

4170C - 24 gauge sheet steel, 0.0250 in. thick, 4 ft X 10 ft, sheet weight = 40 lb.

4170D - poor douglas fir timber, 21 - 4X4 pieces, 5 ft long @ 19 lb/piece.

4170E - gauge 22 corrugated steel, 0.0299 in. thick, three layers (together approximately equal to 13 gauge), 27.5 in. X 12 ft, sheet weight = 37.5 lb.

4170F - good douglas fir timber, 21 - 4X4 pieces, 5 ft long @ 19 lb/piece.

The amount of vertical deflection of the closure material due to the blast wave is dependent on size of the opening, thickness of the material, amount of soil friction holding down the closure, soil arching, whether elastic or plastic response, and other variables.

CONSTRUCTION

All closures were covered with 18 in. of soil berming. See Figure 5-4. Figures 5-5 through 5-7 are photographs taken before the blast. Figure 5-5 shows a displacement gauge, used to assess particle velocity under blast loading.

Both the good and poor timber closures consisted of placing 21 pieces, each 4X4, five feet long, side by side, and then placing and nailing 1/2-in. plywood over the top to ensure they acted as a unit. The plywood was nailed to the two extreme pieces of 4X4. These timbers were common grade stock, sorted at the site into a poor and a good lot for the two different openings.

The corrugated steel pieces were 27.5 ft X 12 ft and consequently, three pieces were required side by side to cover the 6-ft opening (see Figure 5-5). Three thicknesses were used for a total of nine sheets. No permanent connections were used between the sheets, but there was a 2.5 inch overlap.

The three closures of sheet steel were set up in the same manner. These closures were "fixed" by attaching with two ¼-in. X 1¼-in. lag screws at each end to 5 ft long 4X4 pieces of wood (see Figure 5-8).

The boxes were all located 475 ft from ground zero. They were placed in holes two feet deep. After the boxes and closures were positioned, native soil was placed over them to provide the 18 in. cover. This soil was left uncompacted except over the corrugated steel closure, where the berm at the leading and trailing edge was compacted.

INSTRUMENTATION

Four displacement gauges were used in each of experiments 4170B, C, D, and E (installed inside the boxes to measure deflection of closures).

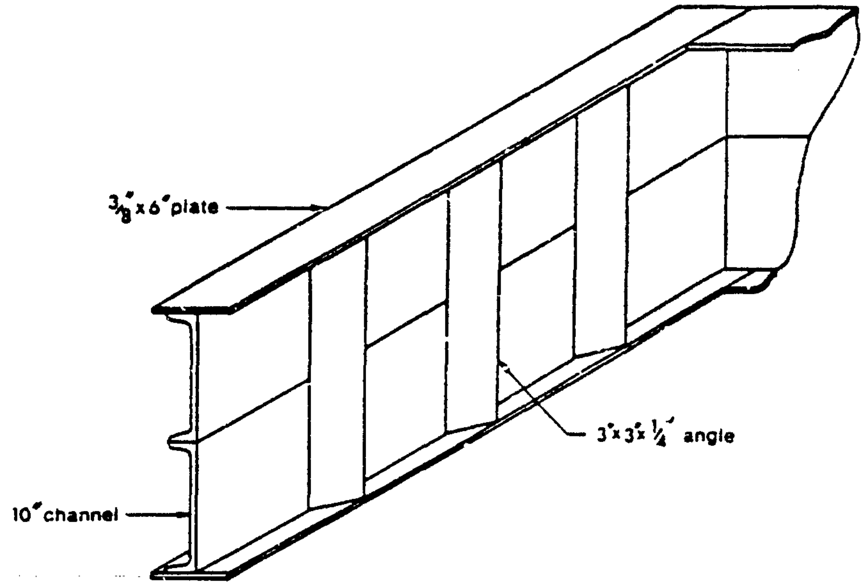


Fig. 5-1. Section View of Box for Experiment 4170.

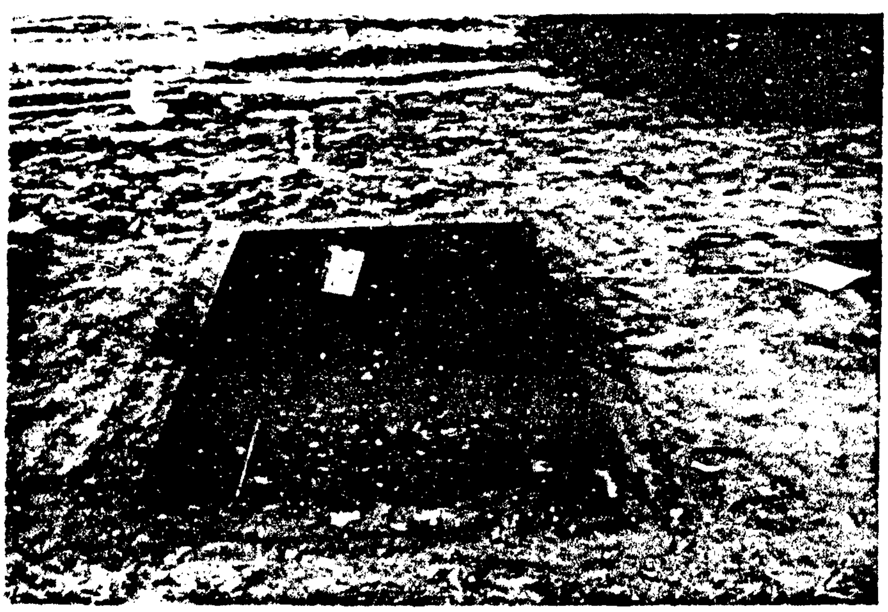


Fig. 5-2. Photograph of Box of Experiment 4170 in Place.

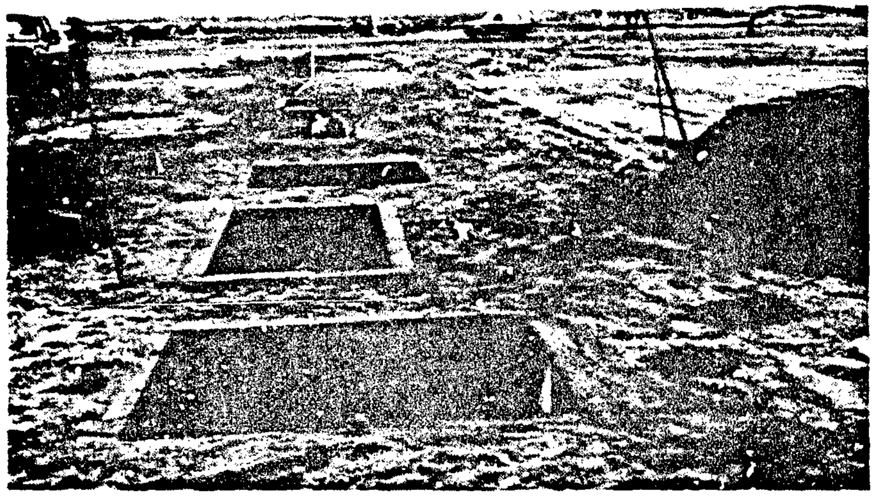


Fig. 5-3. Layout of Boxes in Experiment 4170.

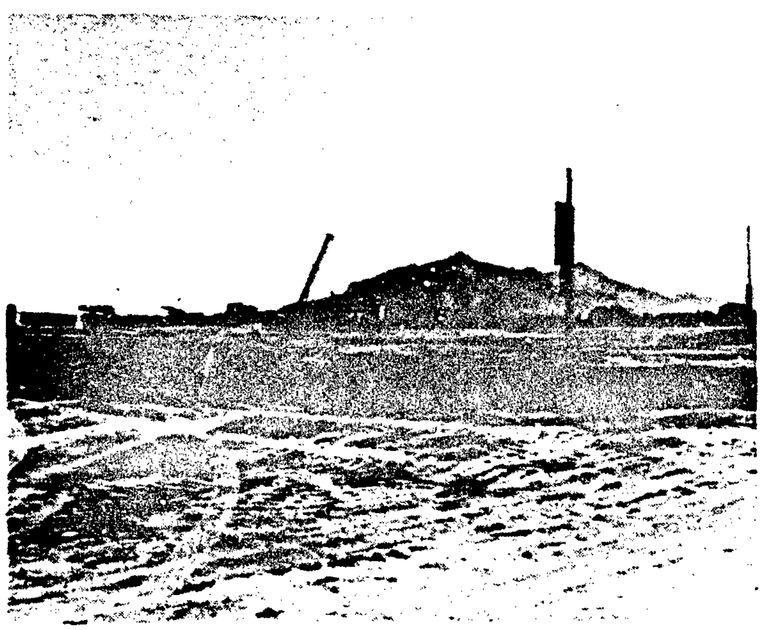


Fig. 5-4. Berm Covering Closures in Experiment 4170.

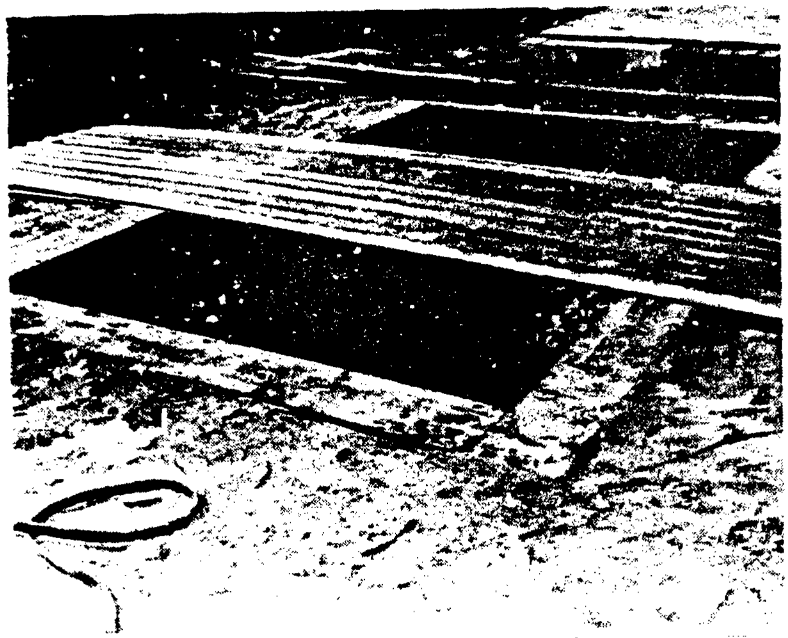


Fig. 5-5. Pretest Photograph of Corrugated Steel Closure (Note displacement gauge).

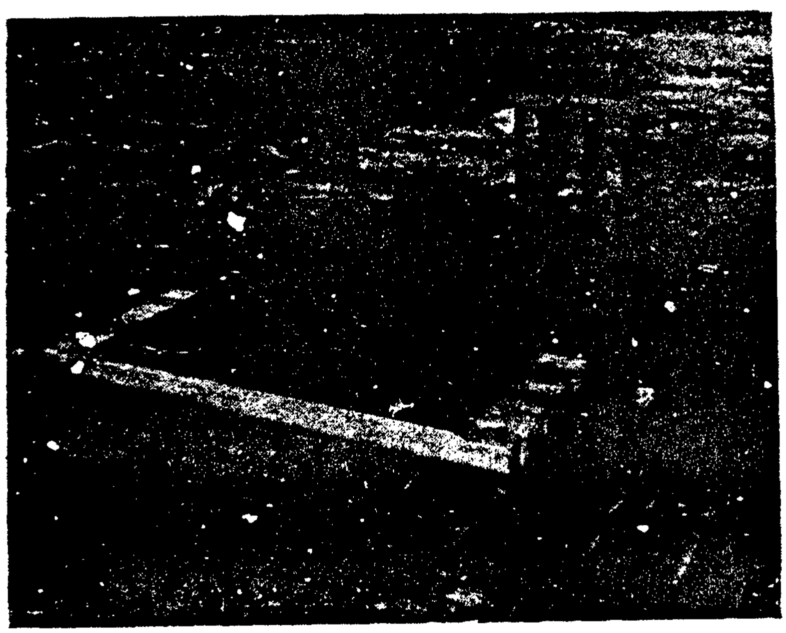


Fig. 5-6. Pretest Photograph of Wood Closure.

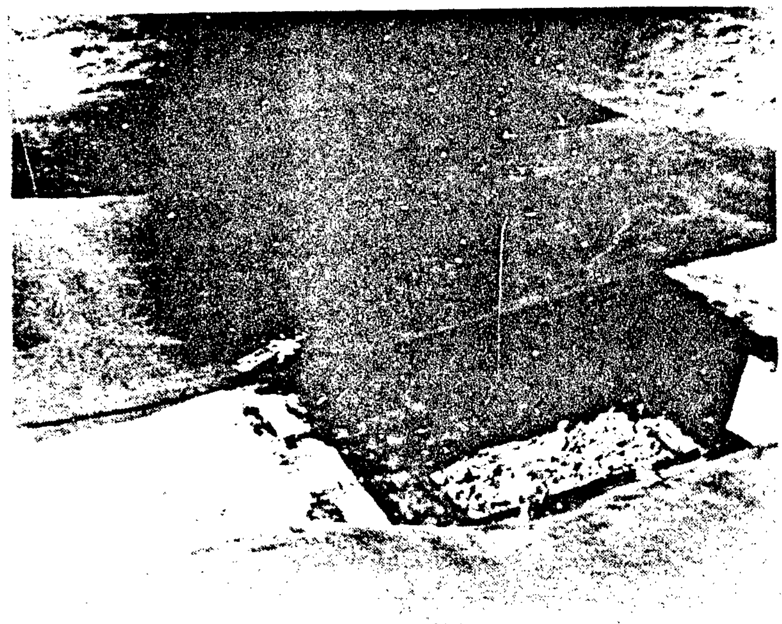


Fig. 5-7. Pretest Photograph of Sheet Steel Closure.

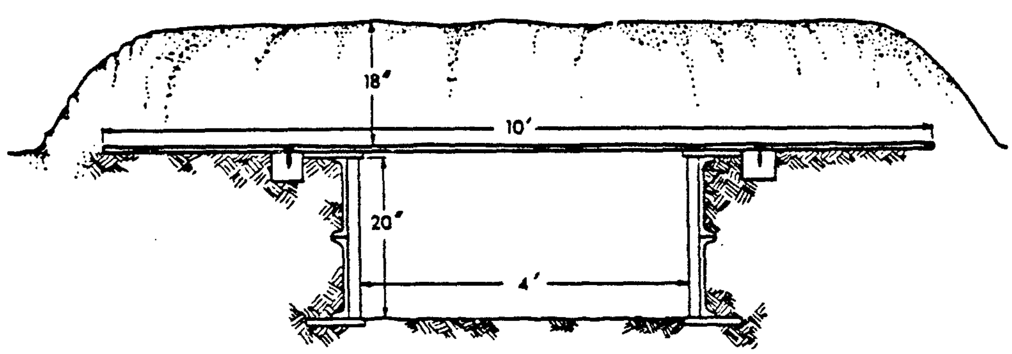


Fig. 5-8. Sketch of Installation of Sheet Steel Closure, Experiment 4170.

TEST DATA, DISCUSSION, AND CONCLUSIONS

The actual pressure in the area of experiment 4170 was approximately 65 psi rather than the predicted 50 psi. Of the six closures tested, three survived, while three failed. Both wood closures responded elastically and survived with no observable damage while the corrugated steel closure responded plastically and had a permanent deflection of approximately 1 ft in the middle of the opening. All three sheet steel closures failed catastrophically.

The displacement gauges were overranged so that deflection data obtained are reliable only for the first inch or two. The displacement vs time plot for the good wood closure, 4170D, shows a deflection of 0.9 inches at the time of 0.026 seconds, with a rebounding deflection (in the negative phase) of -0.4 inches at 0.14 seconds, (see Figure 5-9). The maximum particle velocity was 94 in./s and occurred at about 20 ms. The calculated maximum deflection for elastic response to a static load equal to the peak overpressure is 0.72 in.; the actual deflection under dynamic load would be expected to be greater and this response is further complicated by the inertia of the soil cover and the added protection provided by the soil arching. In any case, these closures, whether the poorer or the better portion of common grade wood, apparently are suitable for 65 psi. See Figure 5-10 for a post-blast photograph. (The irregular pattern on the plywood sheet is a shadow from the edge of the adjacent berm.)

The corrugated steel closure's response to the blast is shown in Figures 5-11, 5-12, and 5-13. Figure 5-13 indicates an initial particle velocity of 98 in./s. The corrugated steel closure has the advantage over sheet steel of added stiffness due to its relatively large moment of inertia. Consequently, even though the three thicknesses of corrugated sheet combined are slightly thinner than the 13 gauge sheet steel, the added stiffness enabled this closure to survive without fixing the ends of the sheets.

Figure 5-14 shows the failed sheet steel closures. As can be seen, the leading edge (the edge closest to ground zero) is deflected up into the air, while the back edge is still in place. A theory for this occurrence is that, as the blast wave passed

over the leading edge of the closure, it imparted energy into the soil and moved it off this edge, which caused the underside of the sheet steel to be exposed to the blast wave and to deflect up when the wave arrived over the opening and pushed the mass into the cavity. The propagating blast wave effectively pinned the back edge, causing it to remain in place, but the leading edge lost its "fixity."

The buildings in which these expedient closures will be used will generally have concrete floors. In such case the sheet steel can be fixed to the concrete quickly with a ramset. It is clear that the corrugated closure will work without such restraint; however, some additional experiments appear to be required to determine just what condition of edge fixity is required for sheet steel closures.

Another difference between the experimental system tested and that which would exist in a shelter situation would be that the entire first floor of a shelter will be bermed. The advantage of this is that the leading edge of the berm will not be so close to the edge of the closure, and thus the soil will not be scarfed up to let the blast wave get under the leading edge and deflect it up. Most likely at the 50 psi overpressure, the PF factor will require a greater depth of soil than the 18 inches used in this experiment, and this improves the beneficial effects of soil arching.

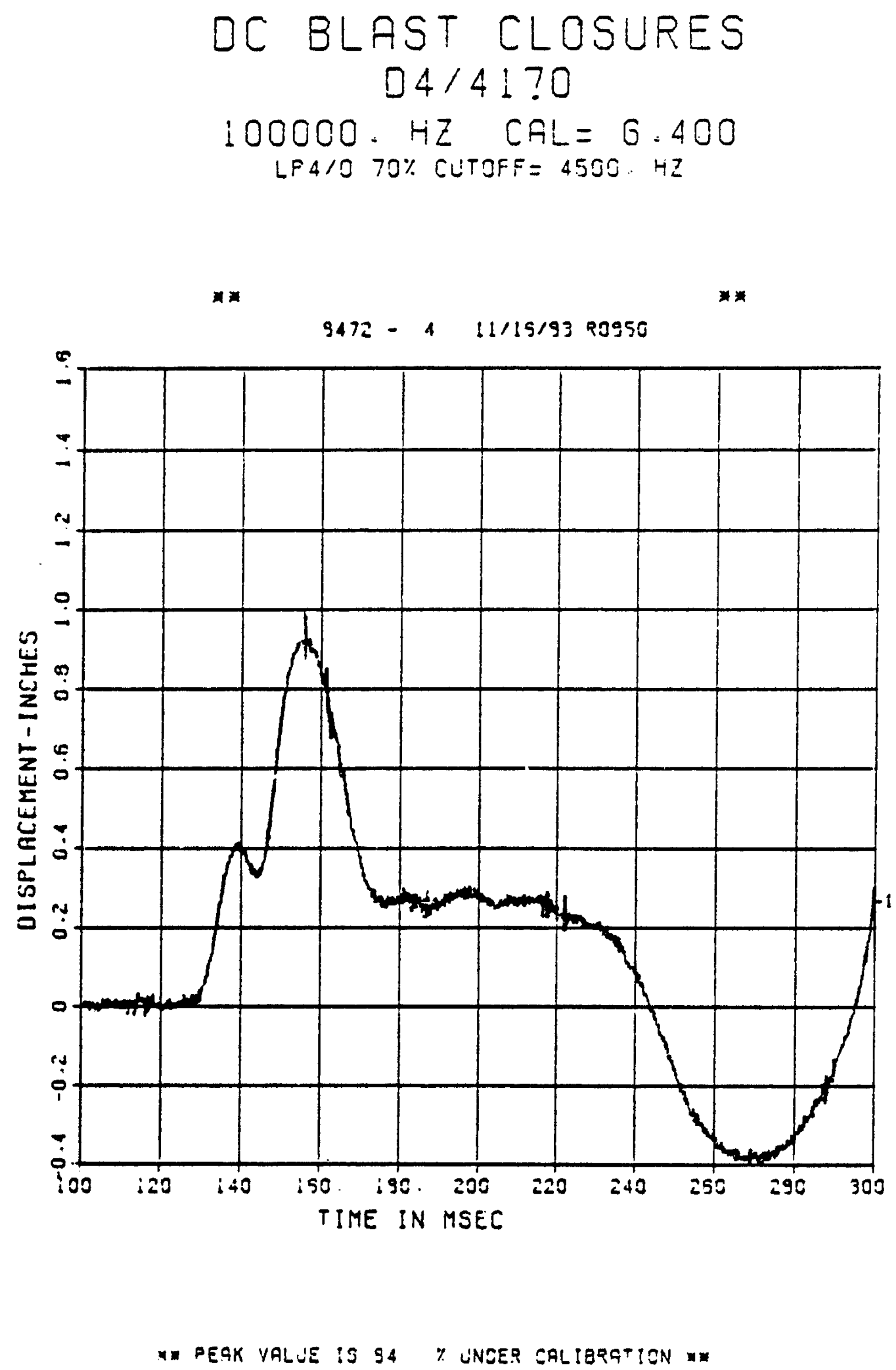


Fig. 5-9. Displacement vs Time Plot for Good Wood Closure, Experiment 4170-D.

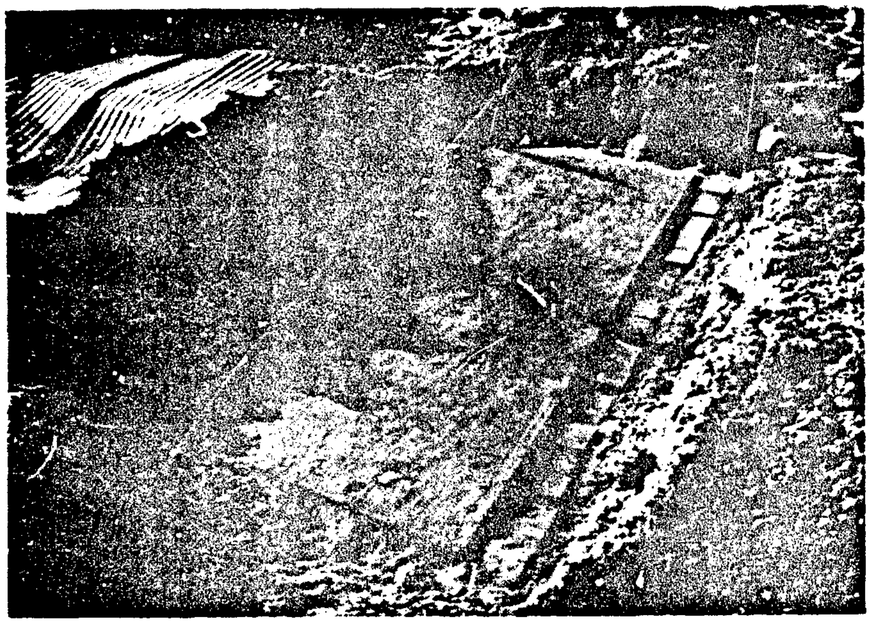


Fig. 5-10. Posttest Photograph of Wood Closure.

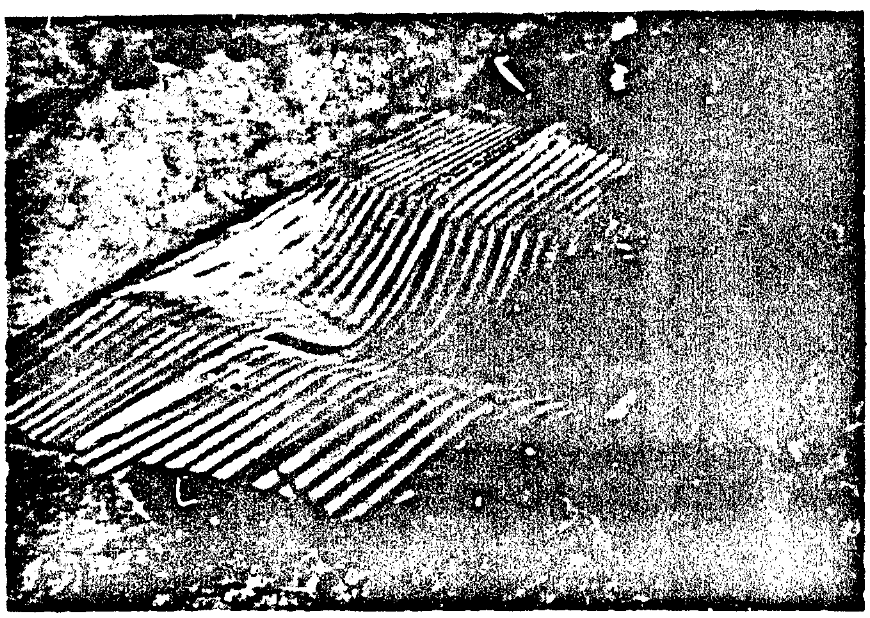


Fig. 5-11. Posttest Photograph of Corrugated Steel Closure.

Fig. 5-12. Posttest Photograph of Corrugated Steel Closure.

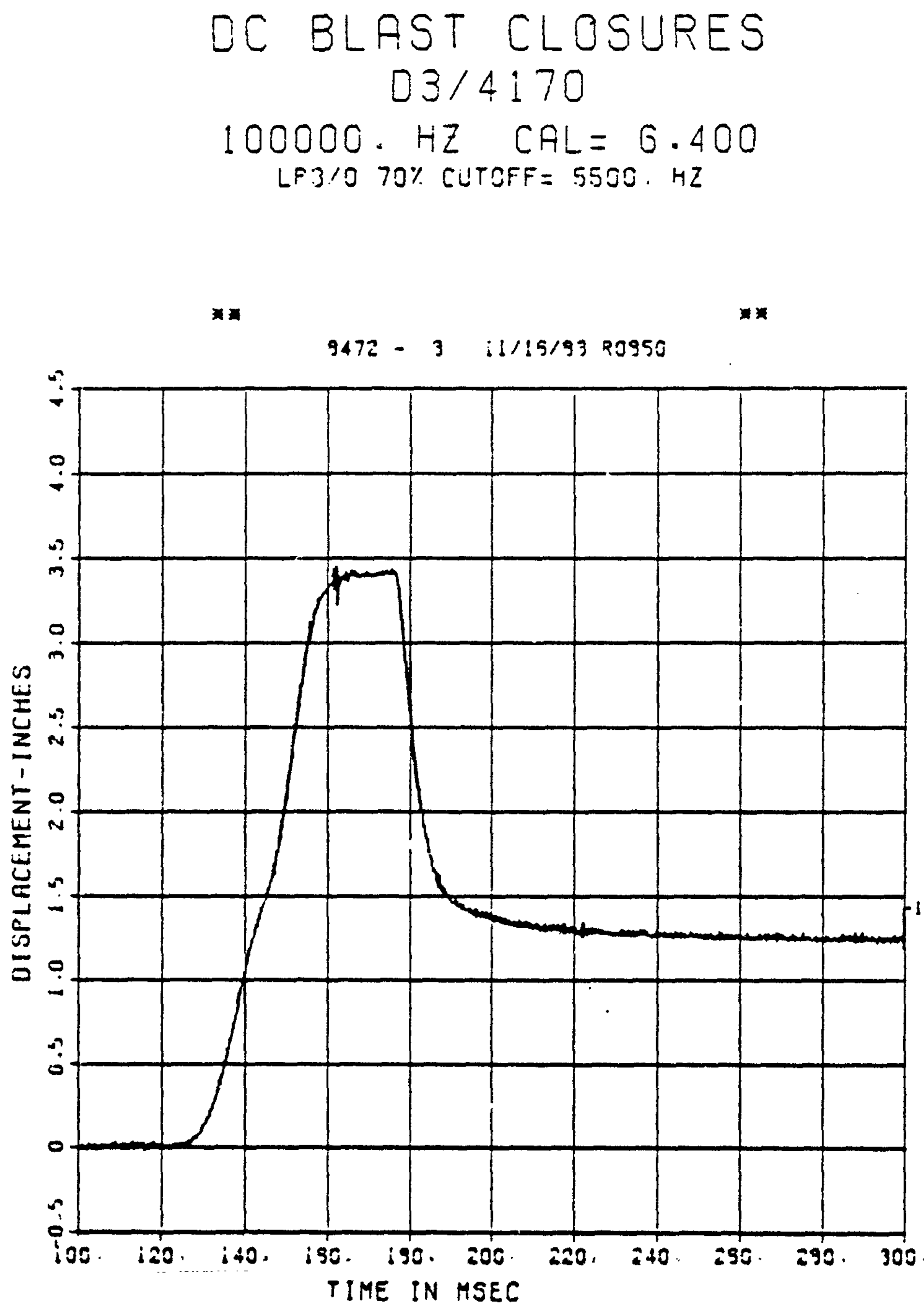


Fig. 5-13. Displacement vs Time Plot for Corrugated Steel Closure.

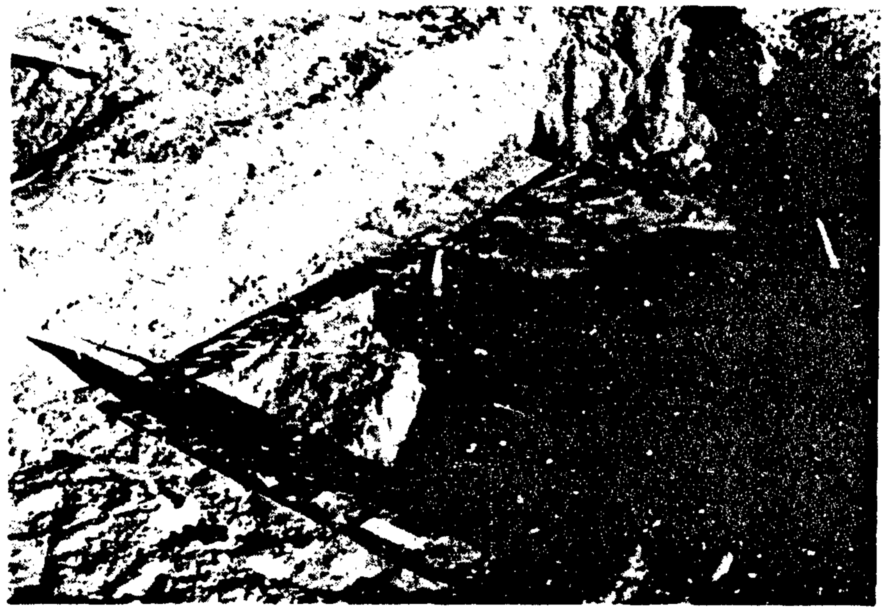


Fig. 5-14. Posttest Photographs of Sheet Steel Closure.

Section 6
MODEL SHELTER TESTS
DNA Nos. 4180 & 4185

INTRODUCTION

The objective of this program was to further test and refine the guidance for the upgrading of two-way reinforced concrete basement ceiling slabs. One important element of the civil defense planning efforts is the development of guidance for the expedient upgrading of existing structures to create shelters, and the design of dedicated shelters for the protection of key workers. This experiment is part of a long series of test programs that have been conducted to develop this guidance including the fielding, during the MILL RACE event, of a full scale basement that tested a number of shoring techniques. Because of financial limitations it was necessary during the DIRECT COURSE event to use scale models. Six reinforced concrete basement ceiling slabs were tested. Three were placed at the expected 50 psi range (Experiment 4180) and three at the 100 psi range (Experiment 4185).

DESIGN

The basement shelters were designed to model an office building at the 50 psi location and a heavy manufacturing building at the 100 psi location. Because the focus of this experiment was on the reaction of the basement ceiling slab, the dimensions and materials for the walls and basement floors of the model shelters were chosen so that they would undoubtedly be able to withstand the impact of the blast. The ground floors had a minimum thickness of two inches, which is 20 inches full scale; welded wire fabric with a diameter of 0.252 inches every 3 inches on center was used for reinforcement. The steel channel walls of the building were also designed to be non-failing.

The model shelter ceilings were designed using the **ACI 318-63 Building Code Requirements for Reinforced Concrete** for two-way concrete slabs on stiff beams and a full scale service moment of 49,500 in.-lbs. The shelters located at the 50 psi range were designed for a live load of 125 psf with a full scale slab thickness of 6.0 inches, which at one-tenth scale was 0.6 inches thick. Those located at the 100 psi range were designed for 250 psf live load and had slabs 8.5 inches thick full scale (0.85 inches tenth-scale).

All six slabs were reinforced with U.S. Standard Gauge 14, at 1 in. on center in both directions, with a wire diameter of 0.0747 inches in order to model a diameter of 0.75 inches every 11 inches at full scale. Additional reinforcement cut at dimensions equal to one-fifth the total span of the slab was placed in the corners of the slabs in accordance with special provisions of the 1963 ACI Code for two-way floor systems with supports on four sides. The shores used were 5/8-inch round steel bars.

CONSTRUCTION

Figure 6-1 shows several views of the model shelter plans. The walls consisted of C10X15.3 channels welded together; on the ground floor D4 welded wire mesh reinforcement was welded to the bottom of these frames (see Figure 6-2). Before the ground floor concrete was poured, the shoring was tied onto the reinforcing fabric with wires and was secured when the concrete was poured. This shoring was either two columns at 8 inches on center for third-point span shoring, or three columns at 6 inches on center for quarter-point span shoring. See Figures 6-3 and 6-4.

The upper concrete slabs were poured into plywood forms (see Figure 6-5) and were transported to the test site in this condition until they could be removed for installation onto the steel frame. The boxes were installed flush with the ground surface and then covered with a thin layer of soil. Figures 6-6 and 6-7 show the models at the test site before the blast.

It was predicted that the two models without any shoring would fail and that the doubly shored systems might fail; the triple shored systems at the both 50 and 100 psi locations were thought to have a reasonable chance of survival.

TEST DATA, DISCUSSION, AND CONCLUSIONS

All six test slabs failed during the blast because of much higher overpressures than expected. Based on measurements taken by WES on nearby experiments the shelters located at the 50 psi location actually received approximately 80 psi, and shelters at the 100 psi location received approximately 118 psi. The presumable cause of the failure was extreme overloading causing punching shear failure in the slab adjacent to the supports. Figures 6-8 and 6-9 show the damage done to the shelters. Note in Figure 6-9 the piece of cable and clamp from the tower, which impacted the unshored shelter. The impact of this piece of debris drove the shelter into the ground approximately 1 inch.

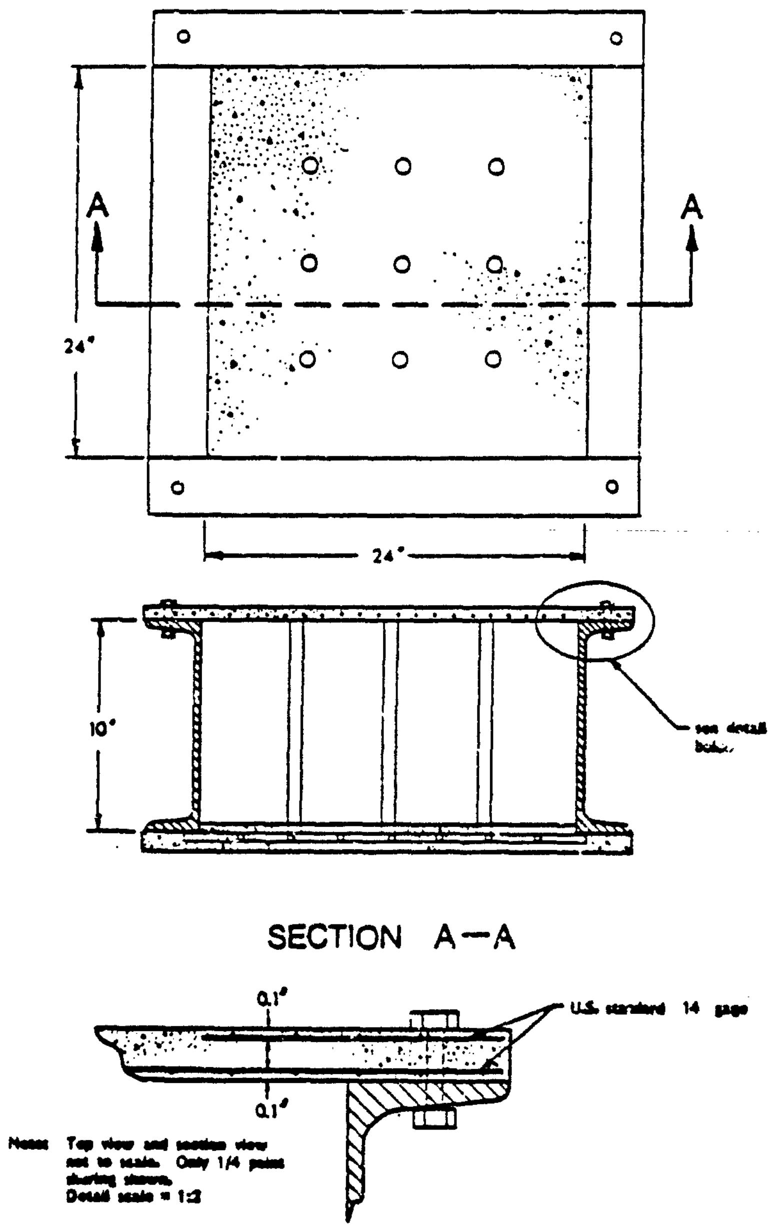


Fig. 6-1. Model Shelter Plans, Experiments 4180 and 4185.

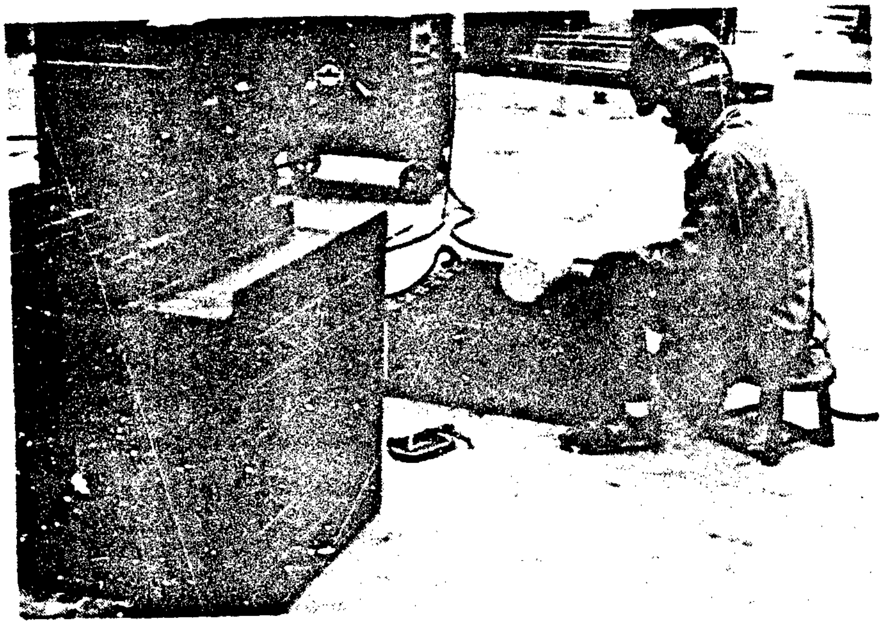


Fig. 6-2. Welding Wire Mesh to Bottom of Frame, Experiments 4180 and 4185.

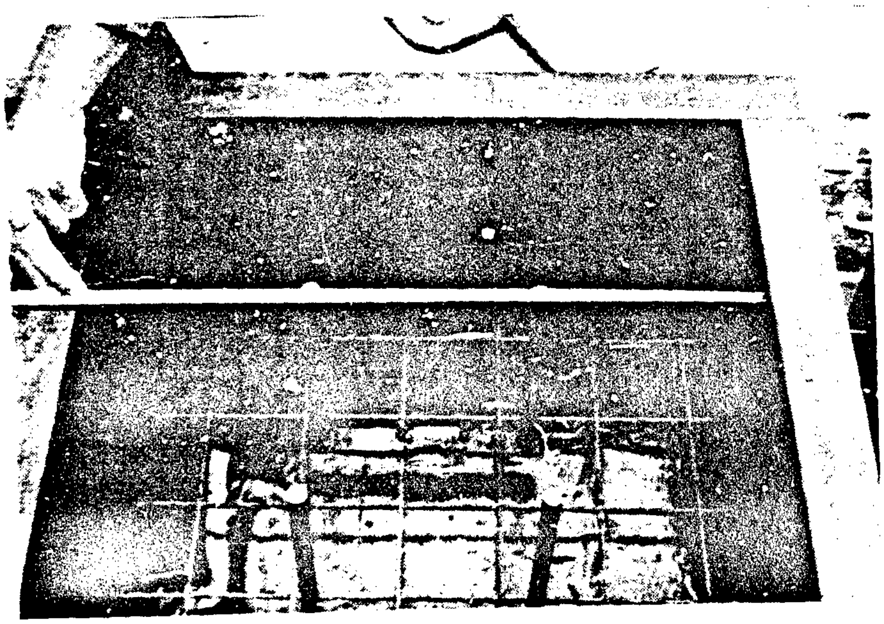


Fig. 6-3. Third-Point Shoring for Experiments 4180 and 4185.

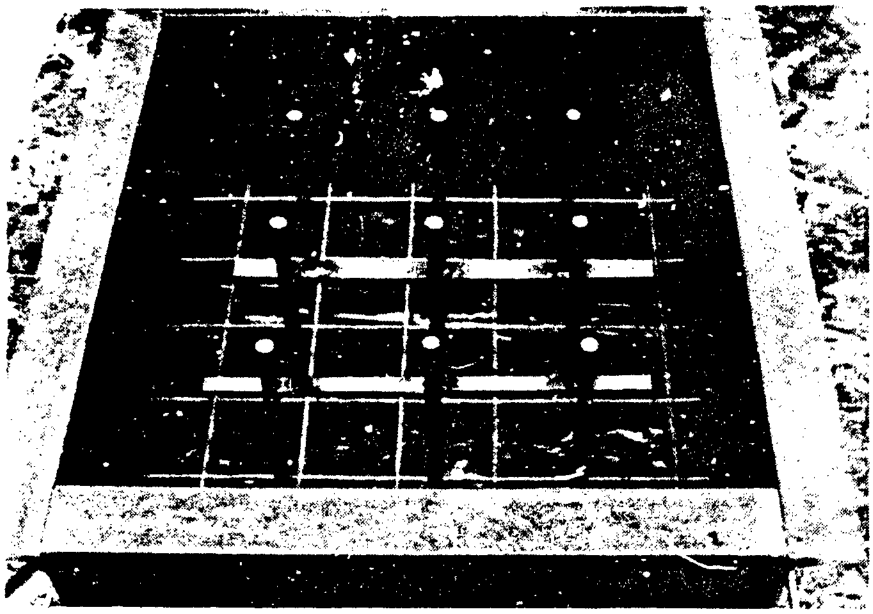


Fig. 6-4. Quarter-Point Shoring for Experiments 4180 and 4185.

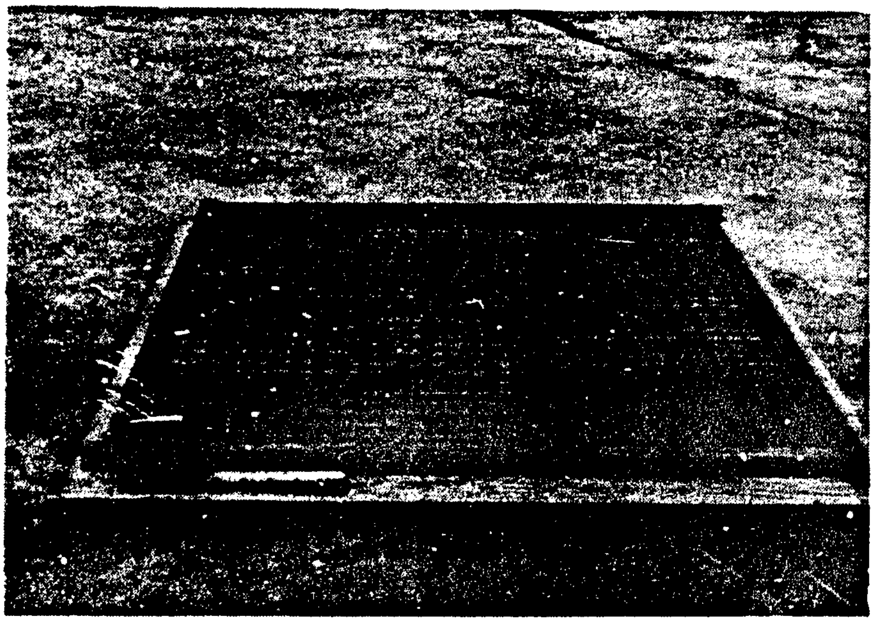


Fig. 6-5. Plywood Form for Upper Concrete Slab.

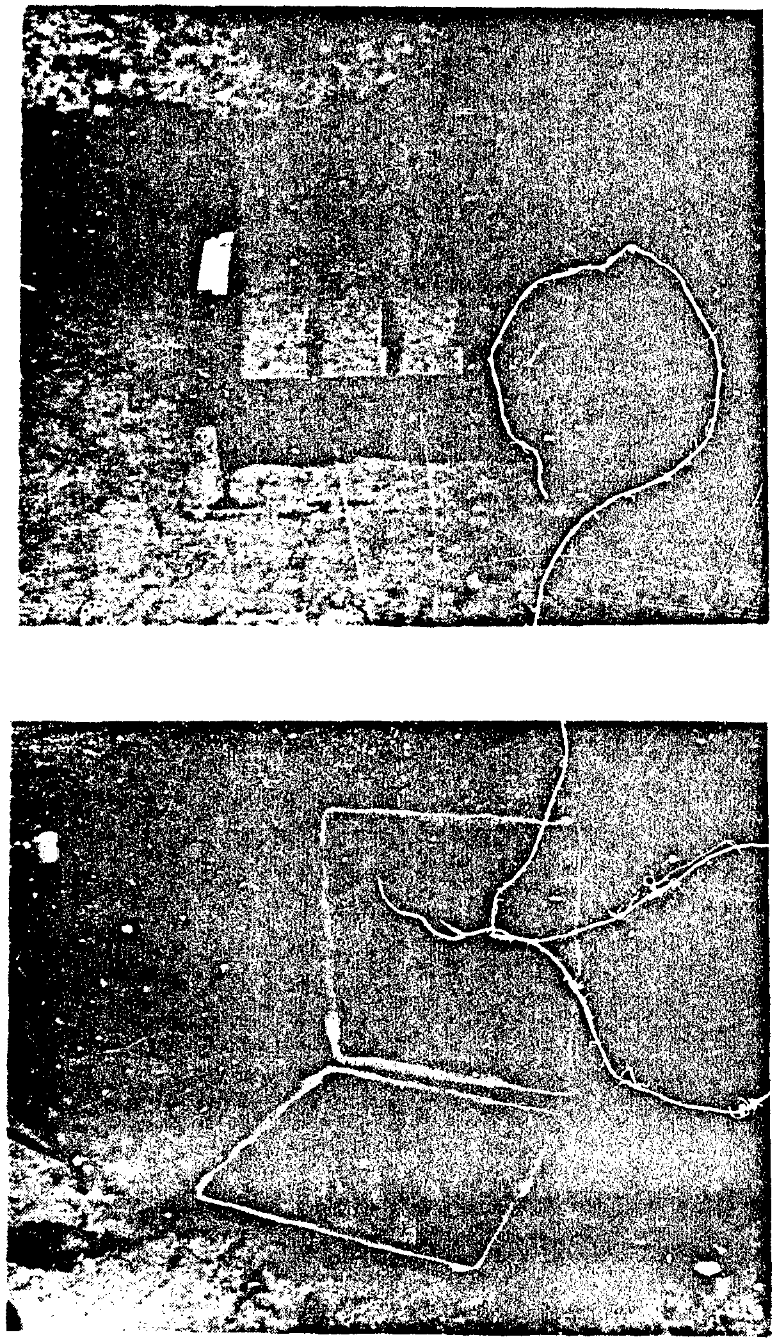
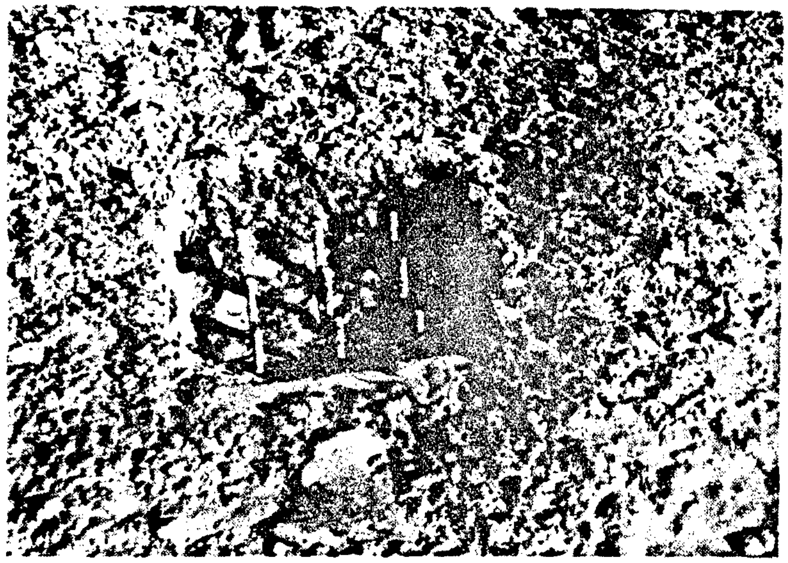
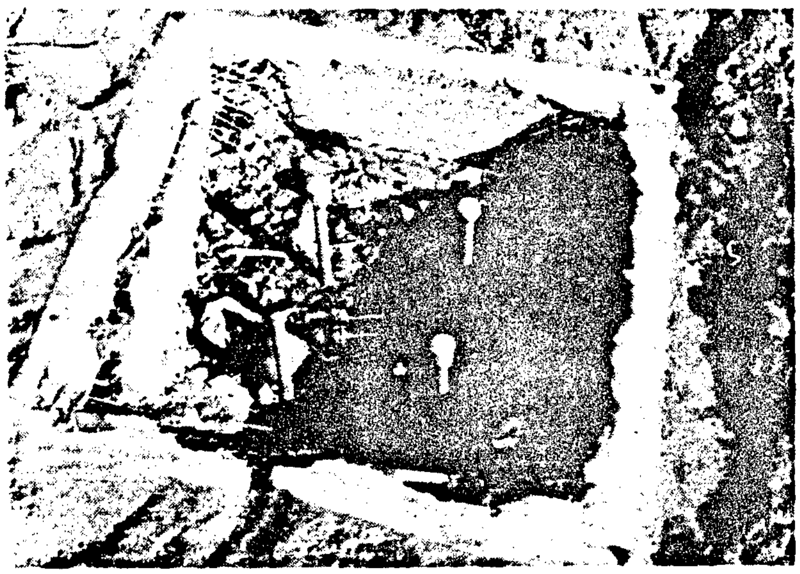


Fig. 6-6. Pretest Photographs of Models Installed at Test Site.

Fig. 6-7. Pretest Photograph of Models Installed at Test Site.





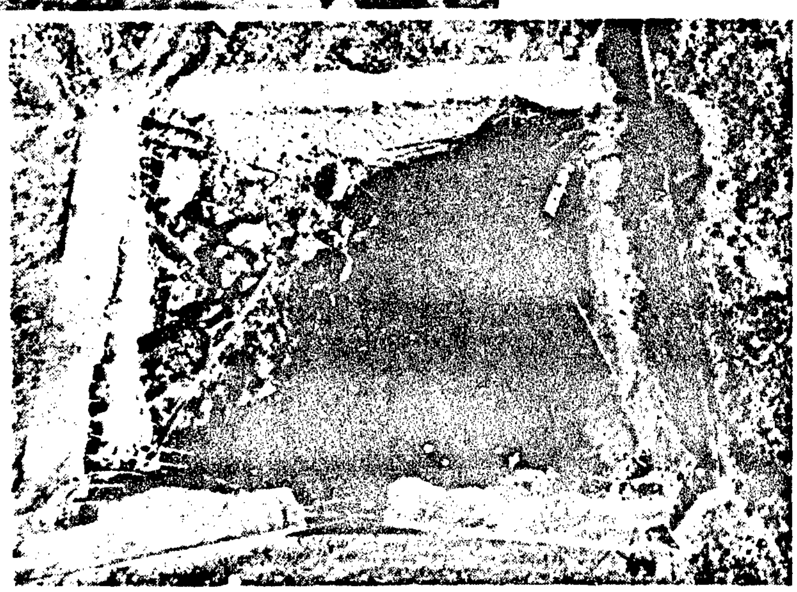


Fig. 6-8. Posttest Photographs of Model Shelters at 50 psi Location.

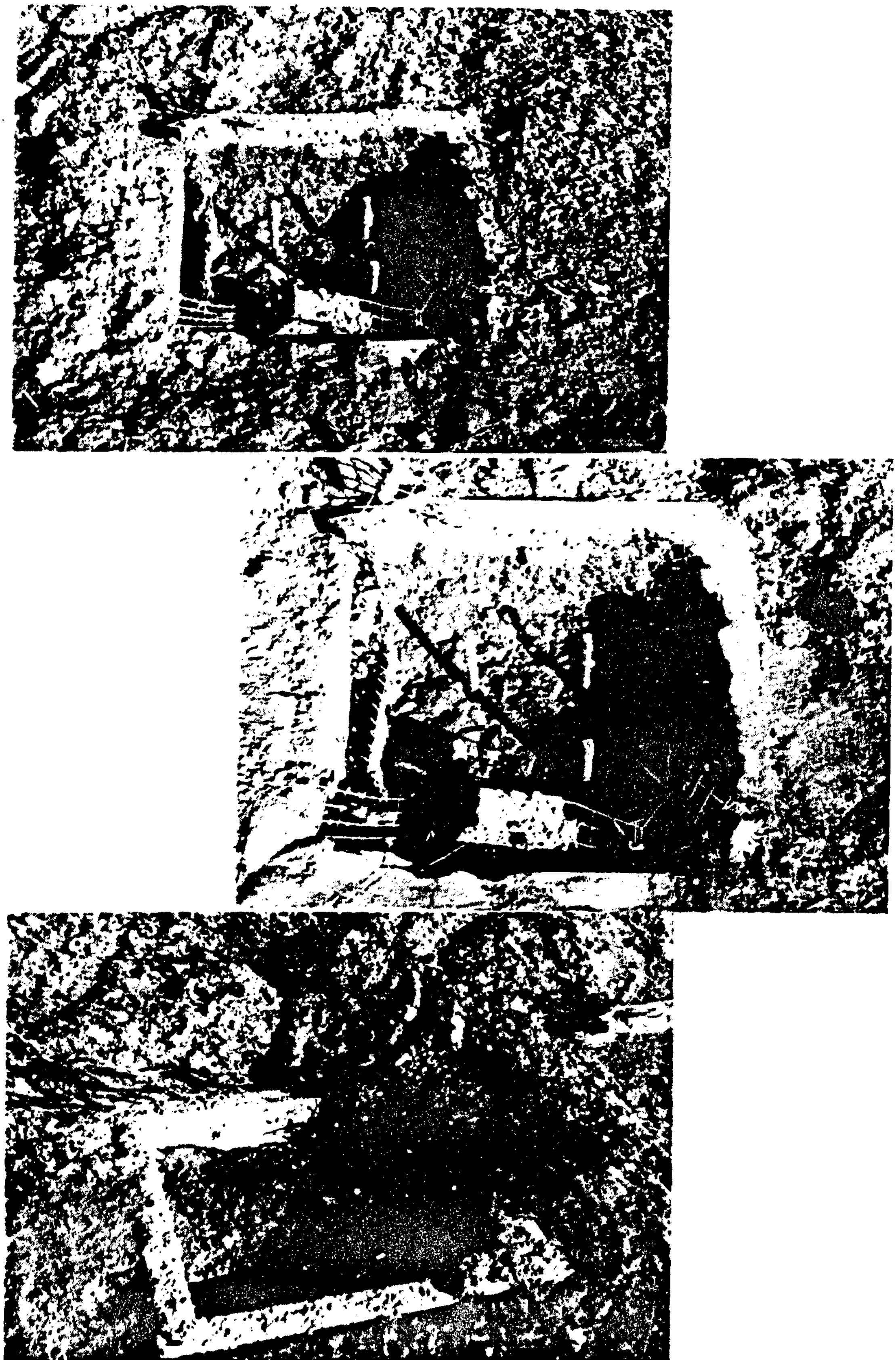


Fig. 6-9. Posttest Photographs of Model Shelters at 100 psi Location.

Section 7
PROGRAM SUMMARY

This section of the report presents a summary of the results of FEMA-sponsored SSI experiments conducted at the DIRECT COURSE high explosive test on October 26, 1983 at White Sands Missile Range, New Mexico. This test was conducted by DNA and consisted of the detonation of 609 tons of ANFO at a height of burst of 166 ft.

Scientific Service, Inc., under the sponsorship of FEMA, designed and conducted experiments at DIRECT COURSE in the areas of industrial protection, shelter design criteria, and model basement walls, closures, and model shelter experiments. The following is a brief description of the results and a summary of the conclusions for these experiments.

INDUSTRIAL PROTECTION EXPERIMENTS

The primary objective of this group of experiments was to gather further experimental data to verify the concept of clustering as a method for the hardening of industrial equipment. In this technique the equipment to be protected is clustered together in an open area, and all items are secured together by means of strapping, banding, etc., with shock-absorbing materials placed between and around the items. The specific objectives were to verify the concept by: (1) Testing of clusters of actual equipment under conditions similar to that for clusters of simulated equipment conducted at the MILL RACE event; (2) Testing of an actual equipment cluster inside a structure where it would be exposed to flying wall fragments; and (3) Testing of simulated equipment clusters (55-gallon drums) under a wider range of conditions than were investigated at the MILL RACE event including higher overpressures, larger clusters, and a wider range of tie materials. Secondary objectives were to further study the behavior of unhardened industrial equipment

under blast loading to determine its vulnerability and to conduct some preliminary tests on hardening methods for electronic equipment.

Two actual equipment clusters, consisting of nine band saws, were tested in the open at approximately 20 psi, one on a concrete pad and one on a dirt pad. In both cases, although the sheet metal legs were damaged beyond reasonable repair, all but one of the pieces of equipment were in good condition and could be rapidly repaired. An additional cluster was tested inside a building and exposed to fragments. In this case, the cluster displaced to a point where one of the main beams of the collapsing building impacted on the cluster, and only three items of equipment survived.

The results from the simulated equipment clusters, 55-gallon drums filled with water, were as follows:

> At the expected 40 psi range (actual pressures 20% to 30% higher) considerable damage occurred; the resulting conclusion was that clustering at this pressure level would not be a practical technique for hazardous materials in drums. This method, applied to rigid equipment with stronger banding techniques, however, might make clustering work at this level.
>
> At the expected 30 psi level (actual pressures somewhat higher) there was also considerable damage due to the drums losing their lids and deforming so that the webbing holding the clusters together loosened and released additional drums from the cluster. It was concluded from the results of this experiment that, at this overpressure range, rigid body items could be successfully clustered if bound with at least the 8,000-pound webbing used; fluid filled drums would also be successfully clustered at this pressure level providing the drums maintained their integrity and remained sealed.
>
> At the expected 20 psi range a variety of binding materials were investigated. It was concluded that a minimum of a 4,000 pound tensile strength binding material was required and that clustering was a valid concept for hazardous materials in drums at this pressure level. It would still be necessary, however, that the lids stay on and the drums retain their integrity.

The tests of the unhardened equipment essentially confirmed the need for using hardening techniques such as the clustering concept. With regard to the electronic equipment tests, a technique of immersing delicate equipment in alcohol proved successful, which suggests that extremely valuable, delicate electronic equipment can be easily hardened to 20 psi.

BASIC SHELTER DESIGN CRITERIA EXPERIMENTS

Two one-fifth scale model buildings, one concrete and the other steel, were tested at the expected 50 psi range (actual overpressure approximately 70 psi). The objective of this test was to obtain information on frame response, building collapse, and survivability of upgraded basements.

The test was successful in that valuable data were obtained on mode of failure and debris translation. Very little data were obtained on frame response, because of problems with the cameras, or on survivability of the upgraded basements, because of the higher than planned overpressures. One of the most important results of this test was the conclusion that valuable information can be gained from structural models of this size in these high explosive events.

MODEL BASEMENT WALL EXPERIMENTS

Eight model basements, each containing three test walls, were tested, six at the expected 50 psi level (actual overpressure approximately 80 psi) and two at the expected 18 psi range (estimated actual overpressure 23 psi). The objectives of this experiment were to test the effects of various types of backfill, to gather statistical data on basement wall collapse and to determine the effect on the loading of the basement walls of the blast wave's reflecting off an aboveground structure.

Because of the higher than planned overpressures, all the walls failed and very little information was gained on the effect of the various types of backfill, and no statistical data were obtained. Significant data were obtained on the effect of the

aboveground structure, however, indicating that even though an aboveground structure does not survive very long, the reflected blast wave off this structure has a significant effect on the overpressure loading on the basement walls.

CLOSURE TESTS

This experiment involved the testing of six types of expedient closures consisting of wood, sheet steel, and corrugated sheet steel at the expected 50 psi range (actual estimated overpressure 65 psi). The objective was to test lightweight closure materials, i.e., materials that could be easily installed by hand.

Of the six closures tested, three survived. These were the good wood, the poor wood, and the corrugated sheet steel. The three sheet steel closures failed, but it was concluded that in a real shelter situation, where they could be fastened down and where soil would be spread over the entire area rather than just on the closures, one or more of those that failed would probably have survived.

MODEL SHELTER TESTS

Six model shelters were tested, three at the expected 50 psi level (actual estimated overpressure 80 psi) and three at the expected 100 psi level (actual estimated overpressure 118 psi). The objective of this experiment was to test the guidance for the upgrading of basements at the 50 and 100 psi levels.

Because of the higher than expected overpressures all the shelters failed.

SUMMARY

In general, in spite of the fact that most of the experiments received higher overpressures than predicted, those data that were obtained were quite valuable and showed outcomes as expected. However, photographic coverage was not as desired.

There were virtually no useful high-speed movies obtained for a variety of reasons. Such movies are extremely critical to understanding and/or analyzing the phenomena not yet well documented or understood. Yet, this is the second test series with totally inadequate high-speed film coverage with the same and more reasons for failures than before, including: not enough dust control, a delay that placed the blast cloud over some of our experiments, water that was ejected from the pool, the structural failure of the most critical camera mounts, and the apparent placing of the cameras on an elastic foundation so that they bounced around inside the mounts giving only momentary glimpses of the event of interest. All of the above were preventable. It is suggested, therefore, that in future events consideration be given to allowing those experimenters who wish to be responsible for their own photography, both still and movie, to do so. Some of the experimenters do have considerable experience in these areas, some of them more than 30 years with substantially better records at overpressures up to 60 psi.

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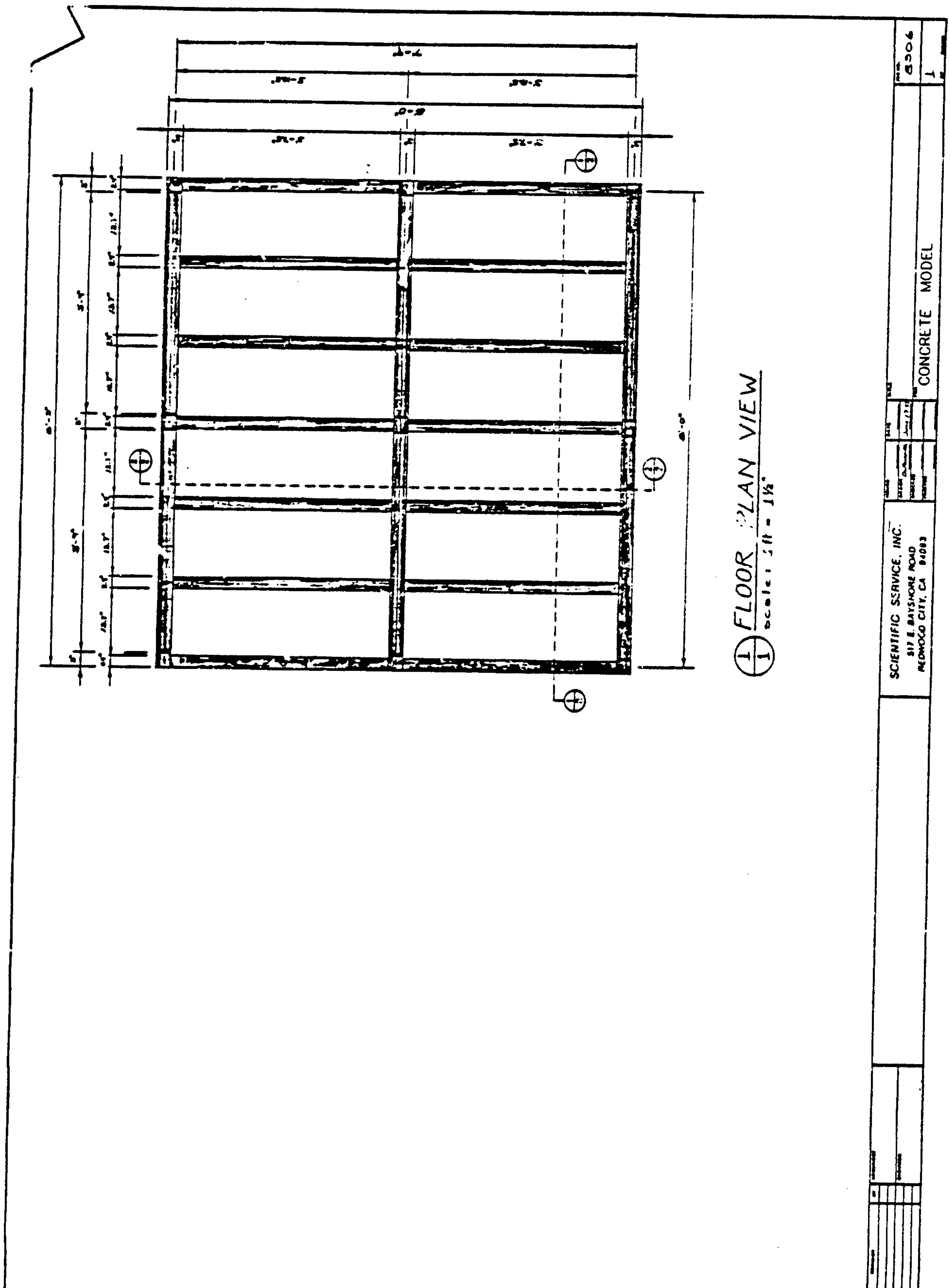
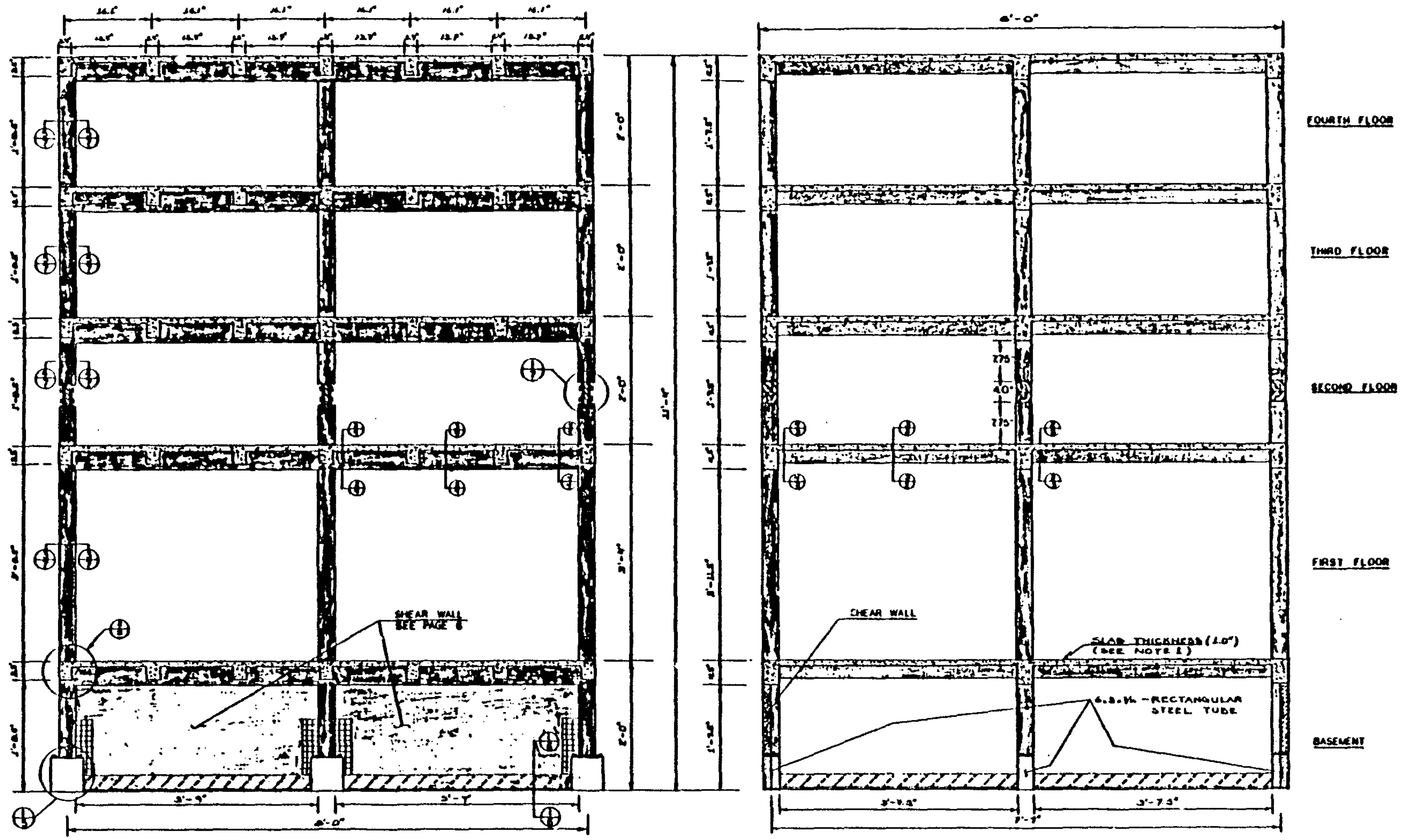
APPENDIX A

DESIGN DRAWINGS FOR EXPERIMENTS 4140 AND 4145


FLOOR PLAN VIEW
Scale: 1ft = 1½"
SCIENTIFIC SERVICE, INC.
517 E. BAYSHORE ROAD
REDWOOD CITY, CA 94063
CONCRETE MODEL
8306



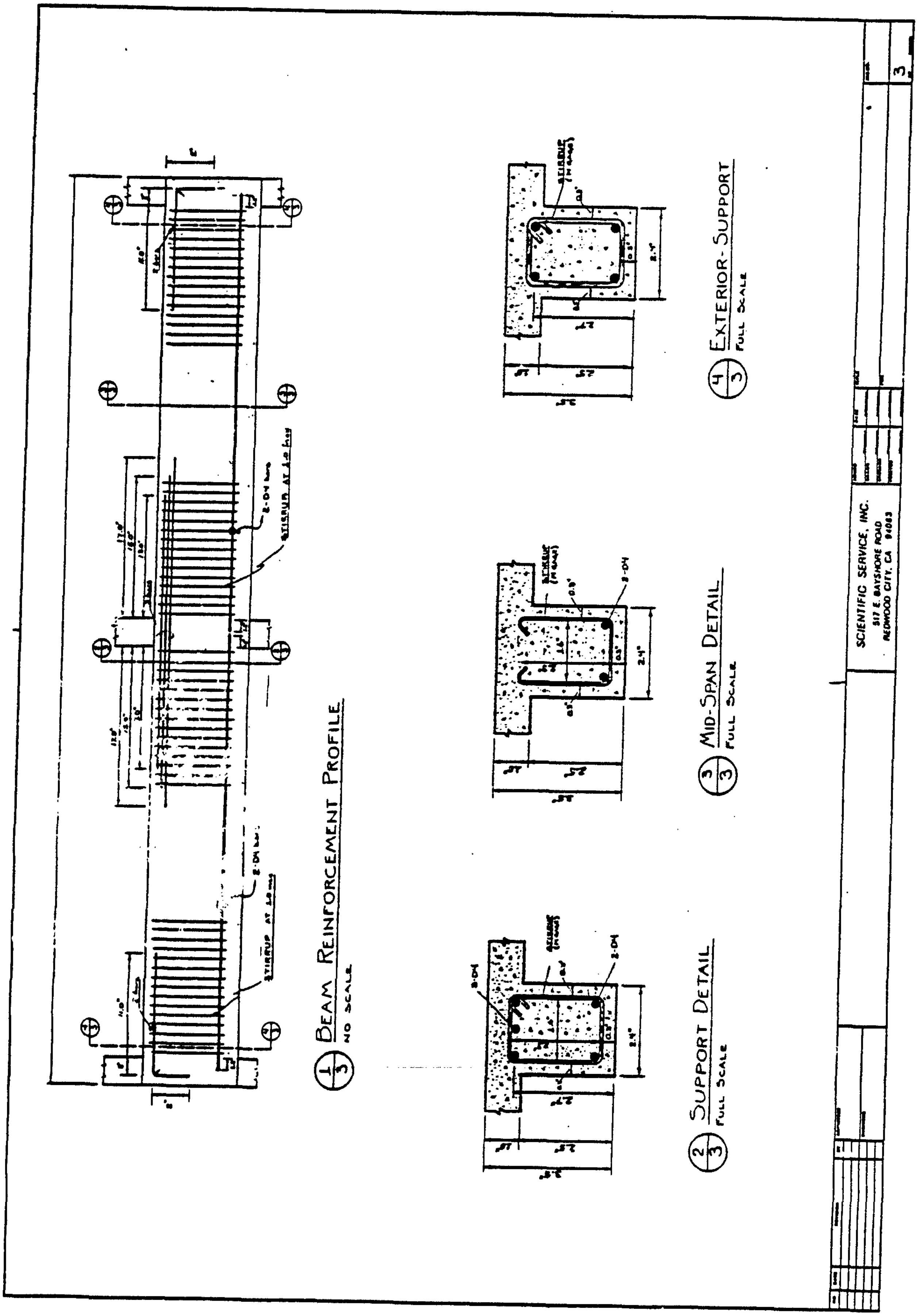
(1/2) GIRDER-COLUMN PROFILE
SCALE: 1 ft = 1½ inches

(2/2) BEAM-COLUMN PROFILE
SCALE: 1 ft = 1½ inches

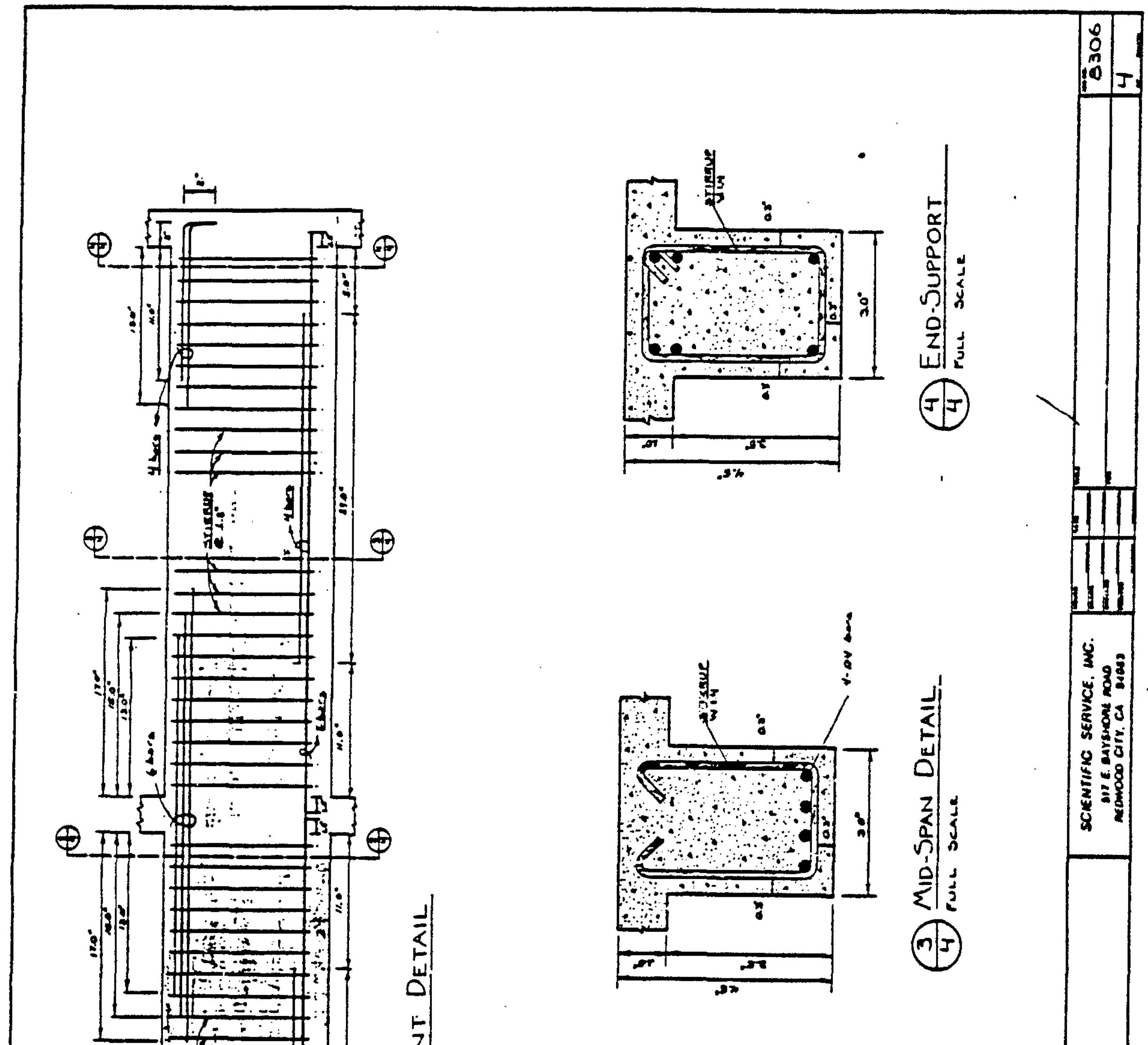
NOTES: 1) SLAB THICKNESS IS THE SAME FOR ALL FLOOR LEVELS (1.0 inch)

SCIENTIFIC SERVICE, INC.
517 E BAYSHORE ROAD
REDWOOD CITY, CA 94063

BUILDING PROFILE
CONCRETE MODEL
8306
2



BEAM REINFORCEMENT PROFILE
NO SCALE
SUPPORT DETAIL
FULL SCALE
MID-SPAN DETAIL
FULL SCALE
EXTERIOR-SUPPORT
FULL SCALE
SCIENTIFIC SERVICE, INC.
517 E. BAYSHORE ROAD
REDWOOD CITY, CA 94063


GIRDER REINFORCEMENT DETAIL
NO SCALE
INTERIOR SUPPORT
FULL SCALE
MID-SPAN DETAIL
FULL SCALE
END-SUPPORT
FULL SCALE
SCIENTIFIC SERVICE, INC.
517 E. BAYSHORE ROAD
REDWOOD CITY, CA 94063
8306
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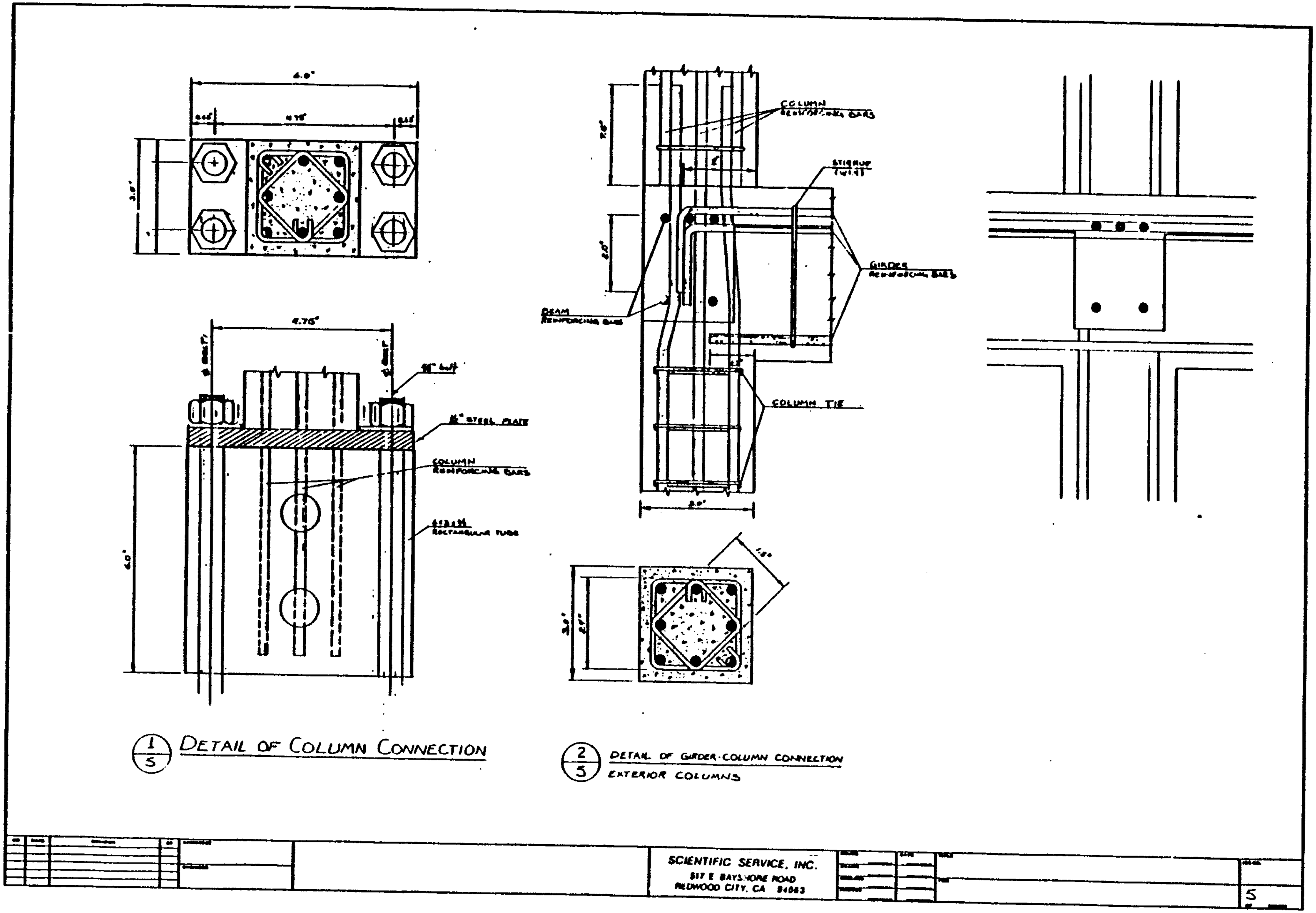

6.0"
4.75"
3.0"
4.75"
5/8" bolt
1/2" steel plate
COLUMN REINFORCING BARS
RECTANGULAR TUBE
6.0"
DETAIL OF COLUMN CONNECTION
COLUMN REINFORCING BARS
STIRRUP
GIRDER REINFORCING BARS
BEAM REINFORCING BARS
COLUMN TIE
2.0"
3.0"
2.4"
DETAIL OF GIRDER-COLUMN CONNECTION
EXTERIOR COLUMNS
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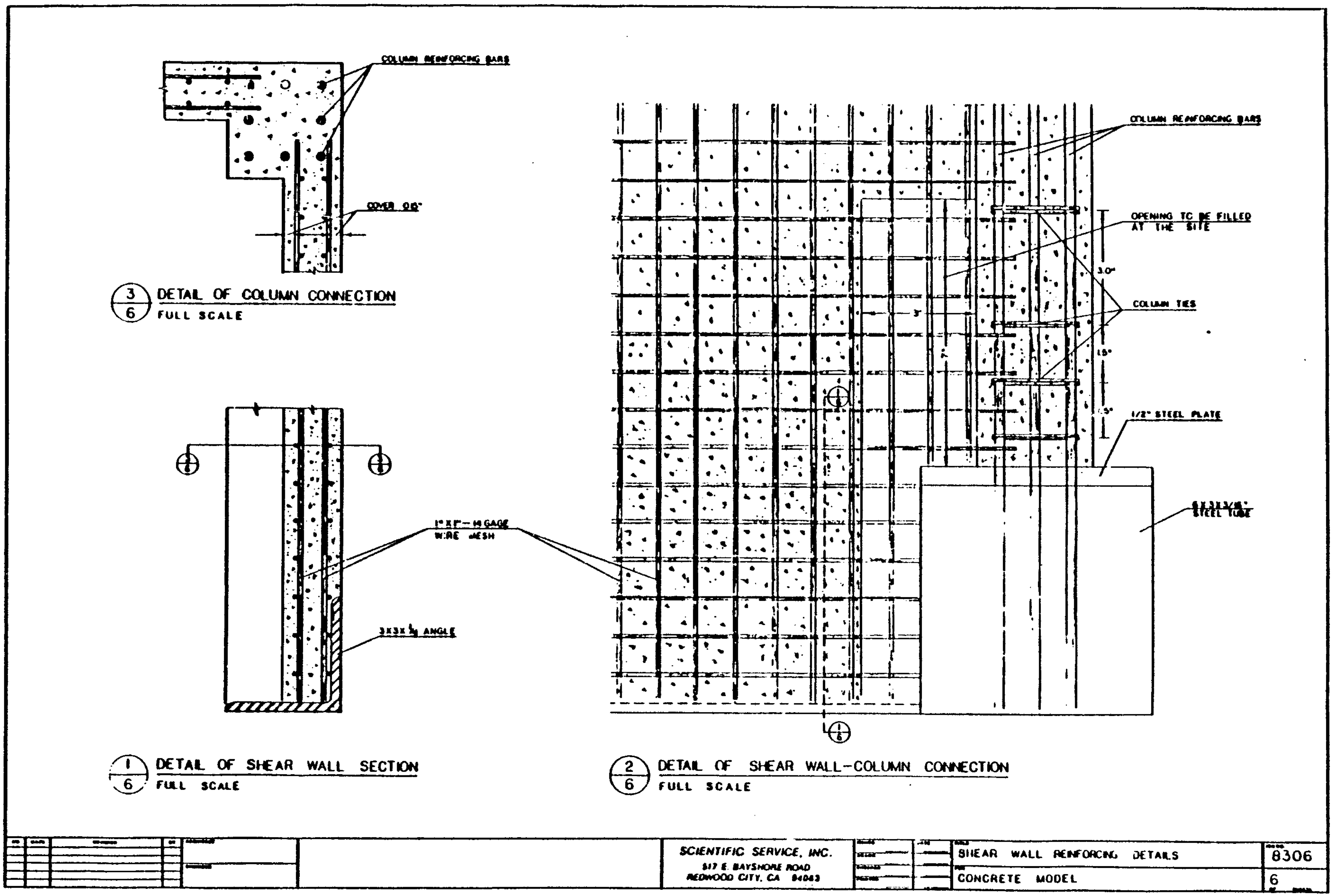
5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COVER 0.6"
DETAIL OF COLUMN CONNECTION
FULL SCALE
1"X1"—14 GAGE WIRE MESH
3X3X1/4 ANGLE
DETAIL OF SHEAR WALL SECTION
FULL SCALE
COLUMN REINFORCING BARS
OPENING TO BE FILLED AT THE SITE
COLUMN TIES
3.0"
1.5"
1.5"
3"
1/2" STEEL PLATE
6X3X3/16" STEEL TUBE
DETAIL OF SHEAR WALL-COLUMN CONNECTION
FULL SCALE
SCIENTIFIC SERVICE, INC.
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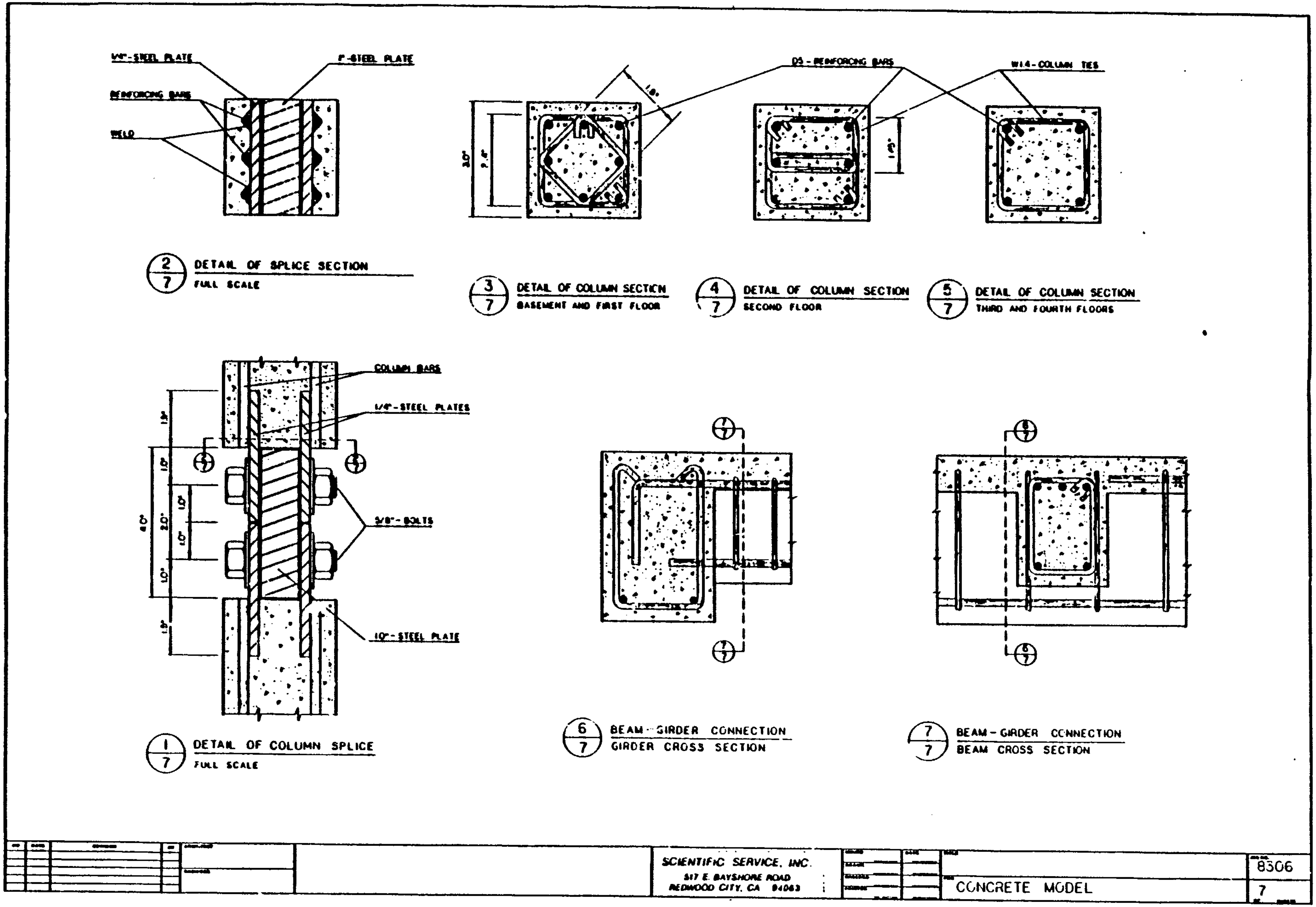
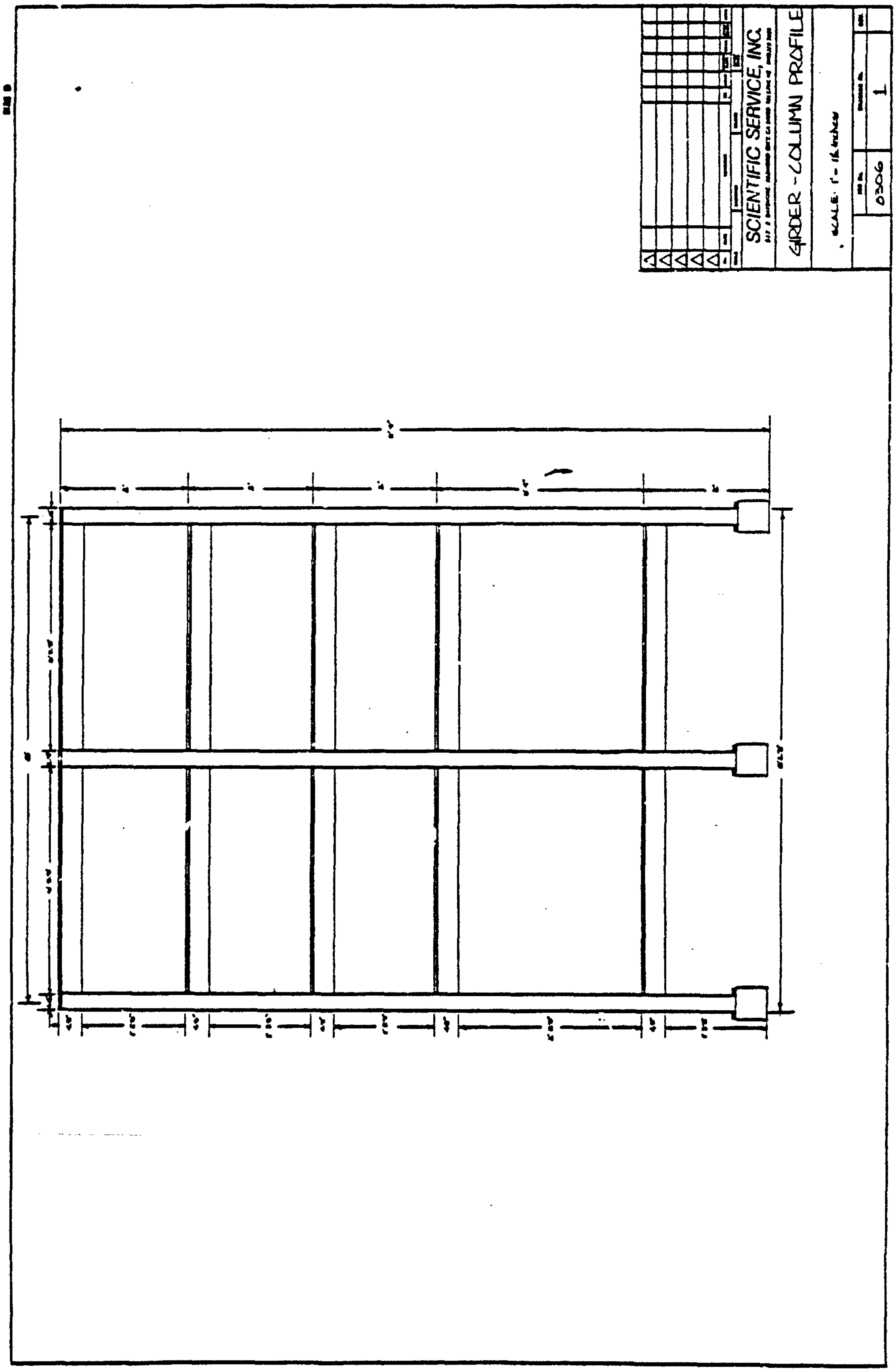
SHEAR WALL REINFORCING DETAILS
CONCRETE MODEL
8306
6


1/4"-STEEL PLATE
1"-STEEL PLATE
REINFORCING BARS
WELD
2/7 DETAIL OF SPLICE SECTION
FULL SCALE
D5 - REINFORCING BARS
W1.4 - COLUMN TIES
1.0"
3.0"
2.4"
1.0"
3/7 DETAIL OF COLUMN SECTION
BASEMENT AND FIRST FLOOR
4/7 DETAIL OF COLUMN SECTION
SECOND FLOOR
5/7 DETAIL OF COLUMN SECTION
THIRD AND FOURTH FLOORS
COLUMN BARS
1/4"-STEEL PLATES
5/8"-BOLTS
1.0"-STEEL PLATE
1.5"
1.0"
2.0"
1.0"
1.5"
4.0"
1.0"
1.0"
1/7 DETAIL OF COLUMN SPLICE
FULL SCALE
6/7 BEAM - GIRDER CONNECTION
GIRDER CROSS SECTION
7/7 BEAM - GIRDER CONNECTION
BEAM CROSS SECTION
SCIENTIFIC SERVICE, INC.
517 E. BAYSHORE ROAD
REDWOOD CITY, CA 94063
CONCRETE MODEL
8306
7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GIRDER - COLUMN PROFILE
SCALE: 1" - 16 inches
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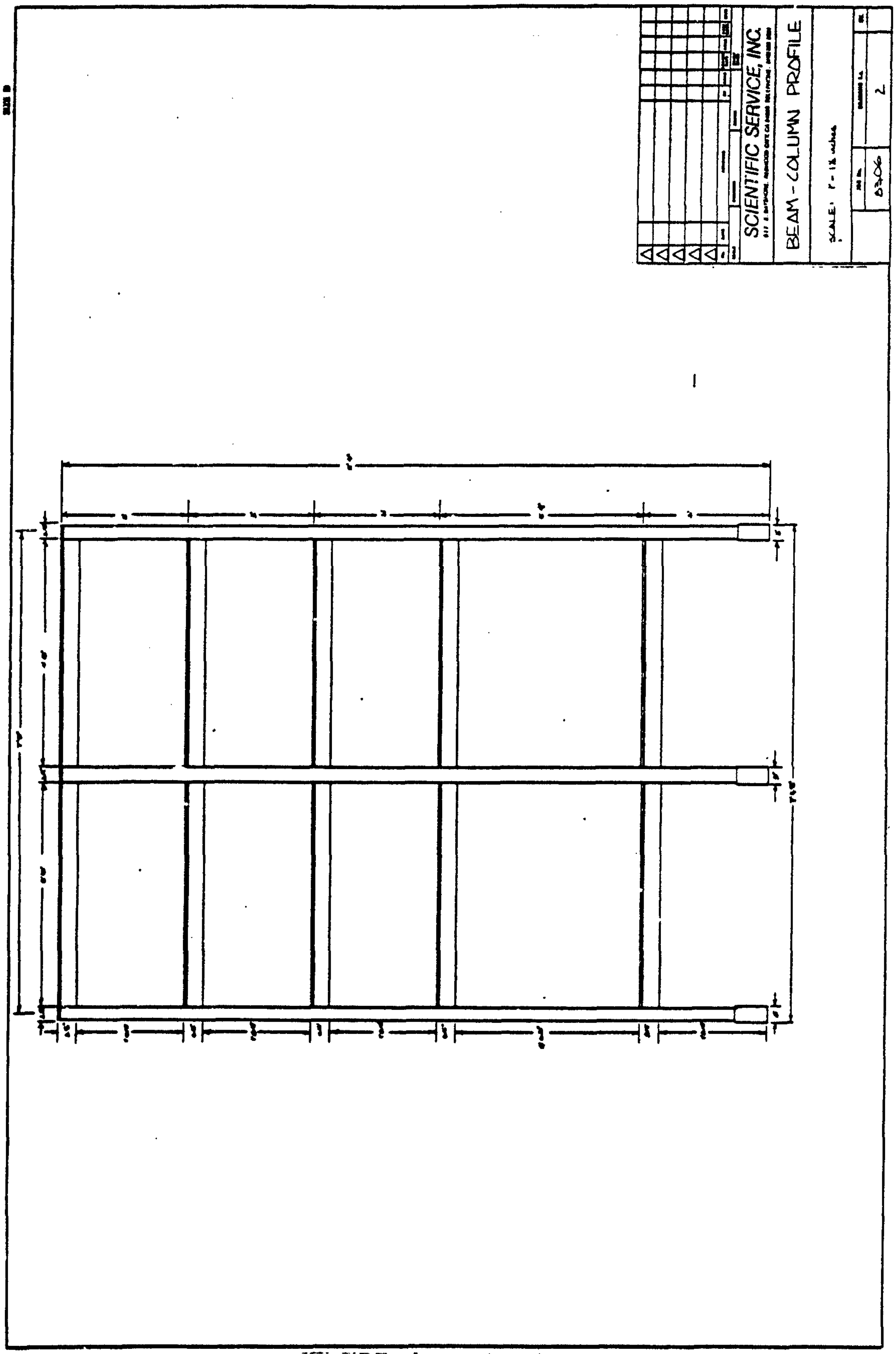
1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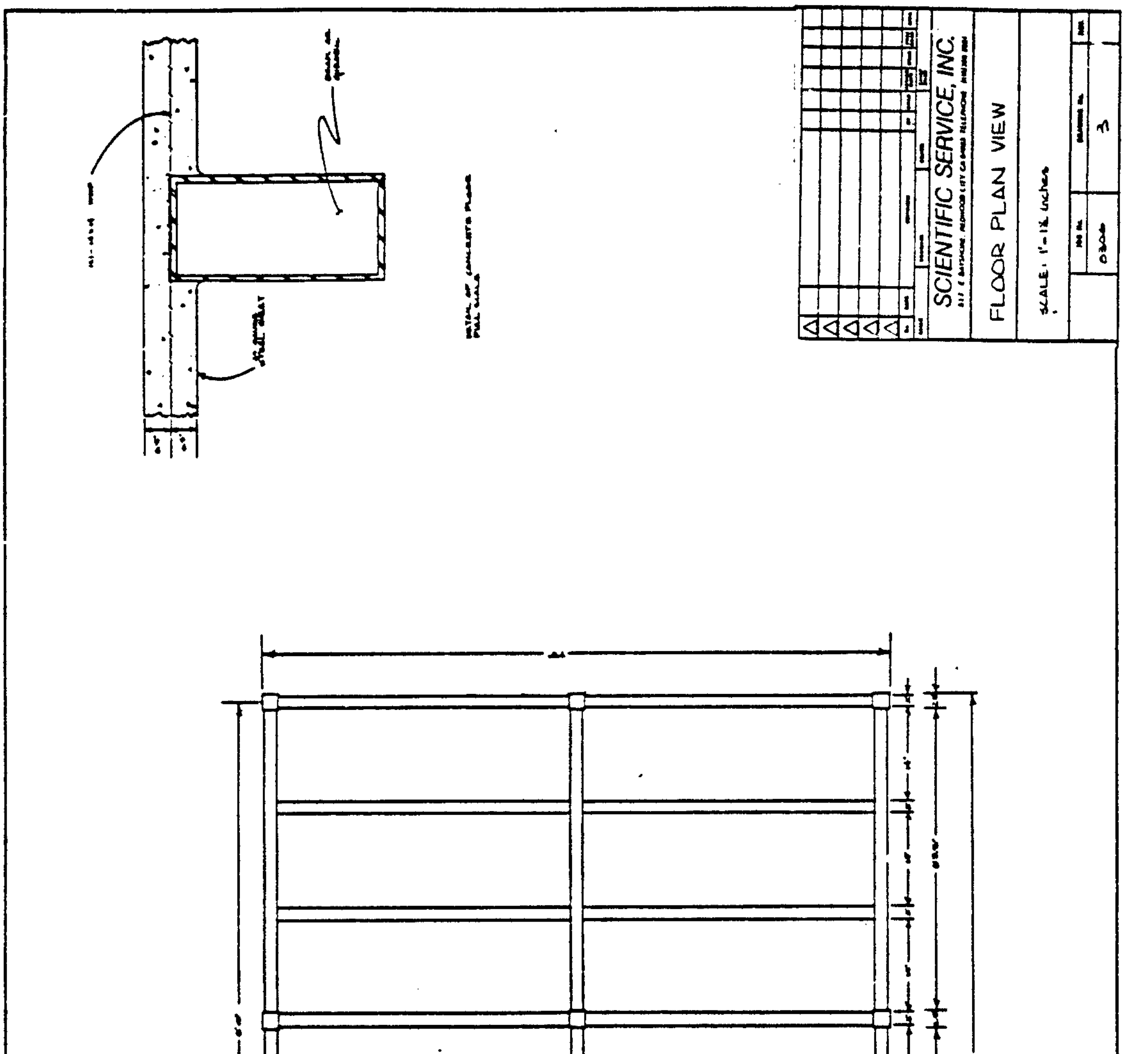
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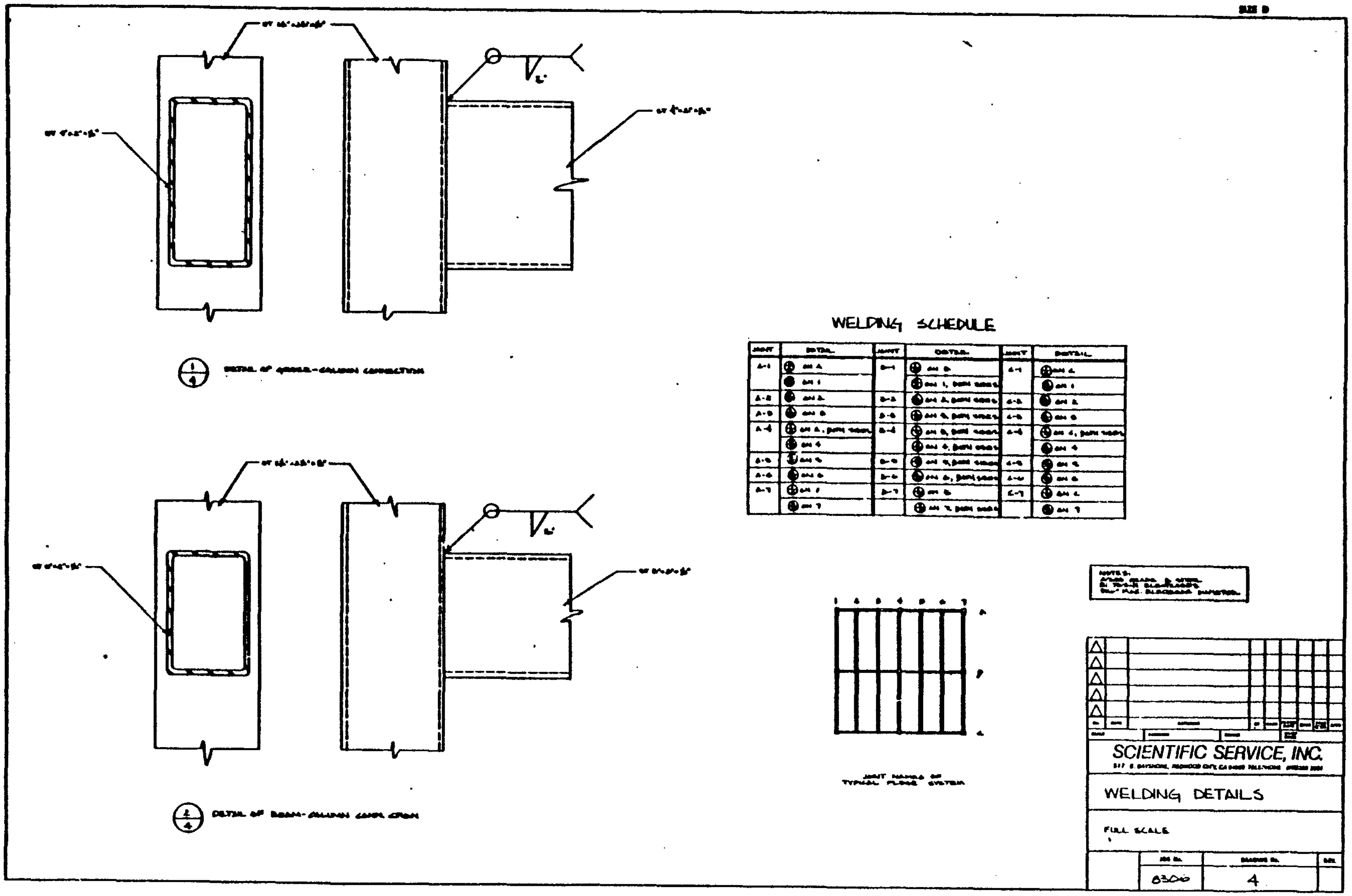
FLOOR PLAN VIEW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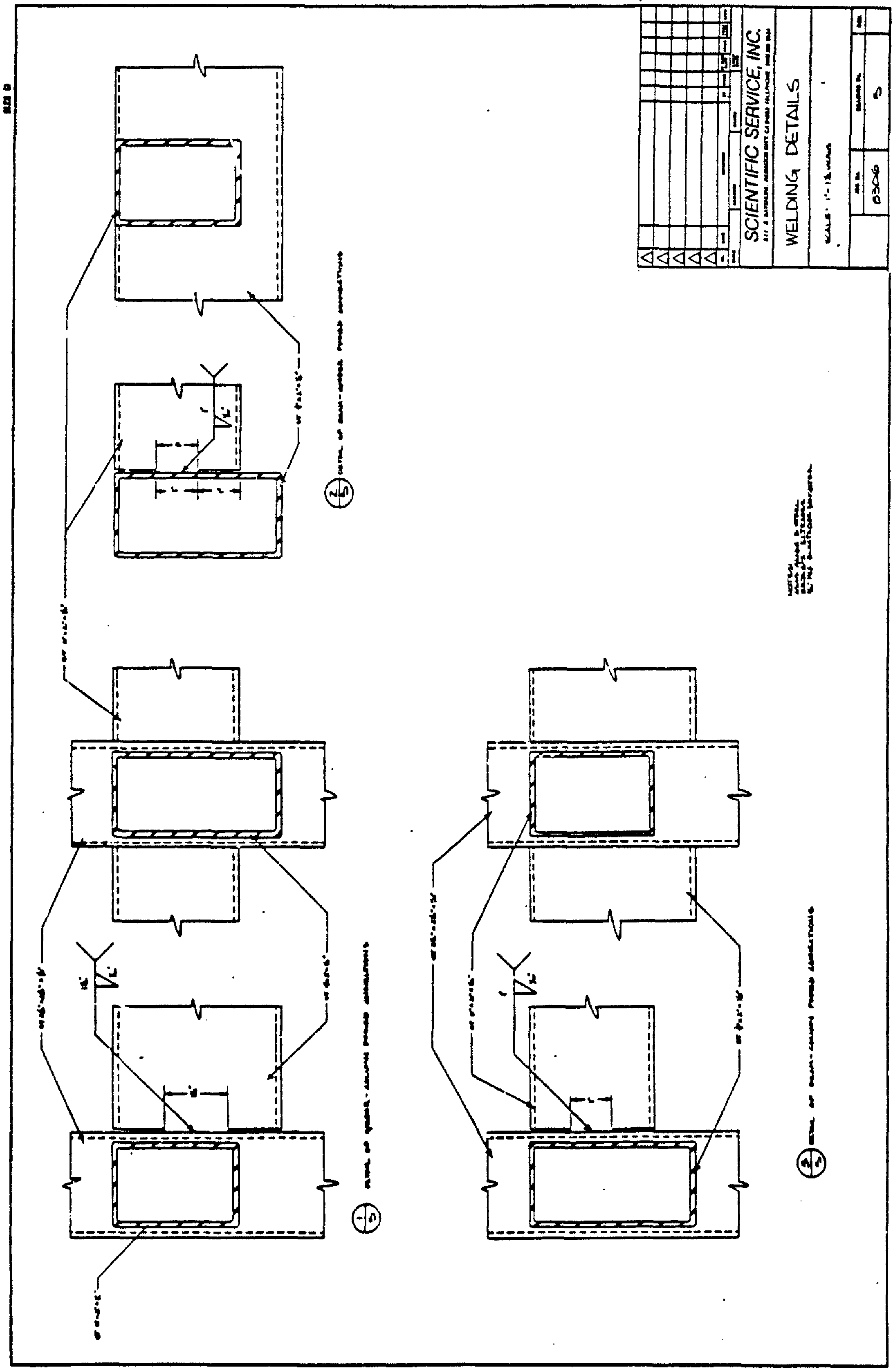
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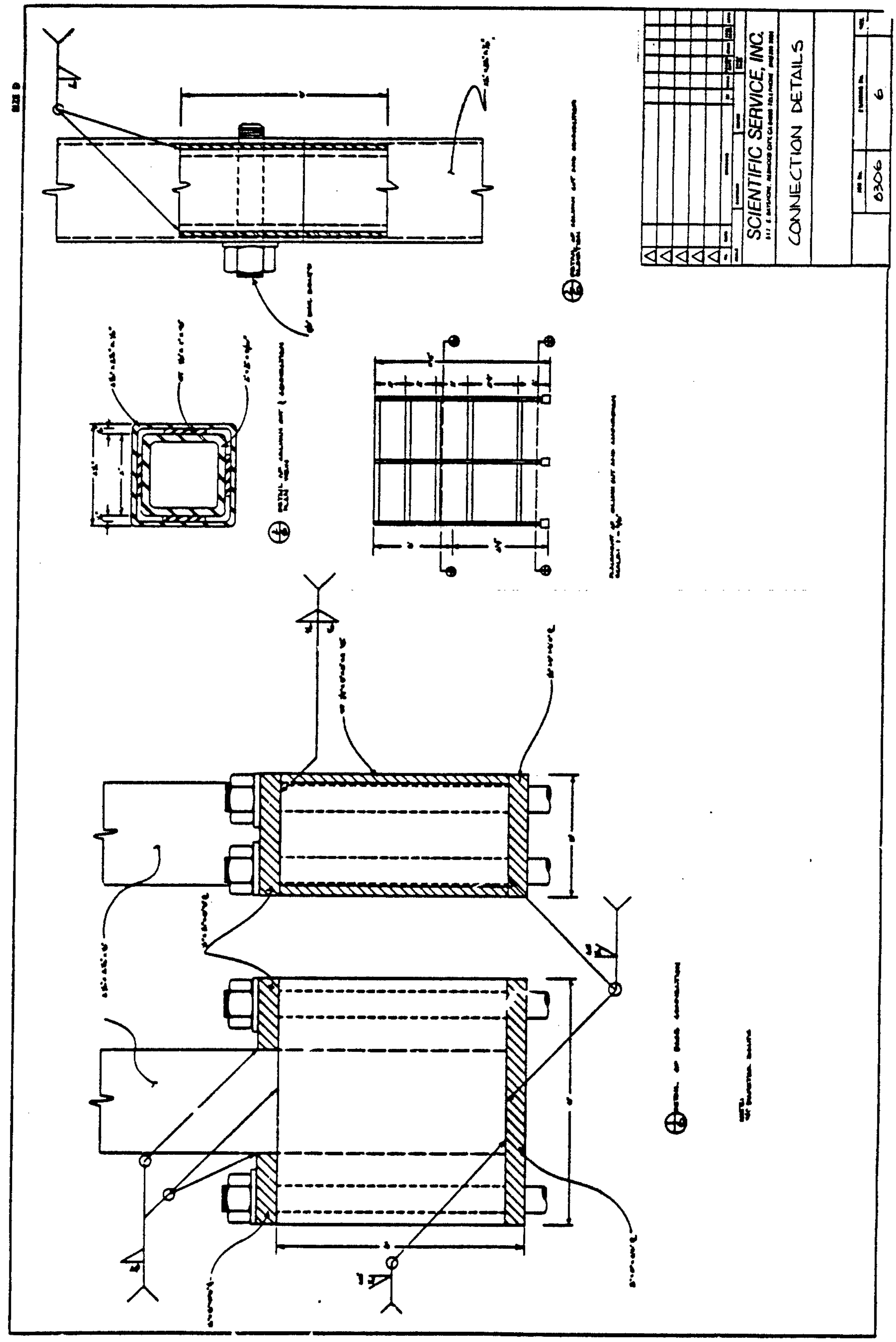
WELDING DETAILS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CONNECTION DETAILS
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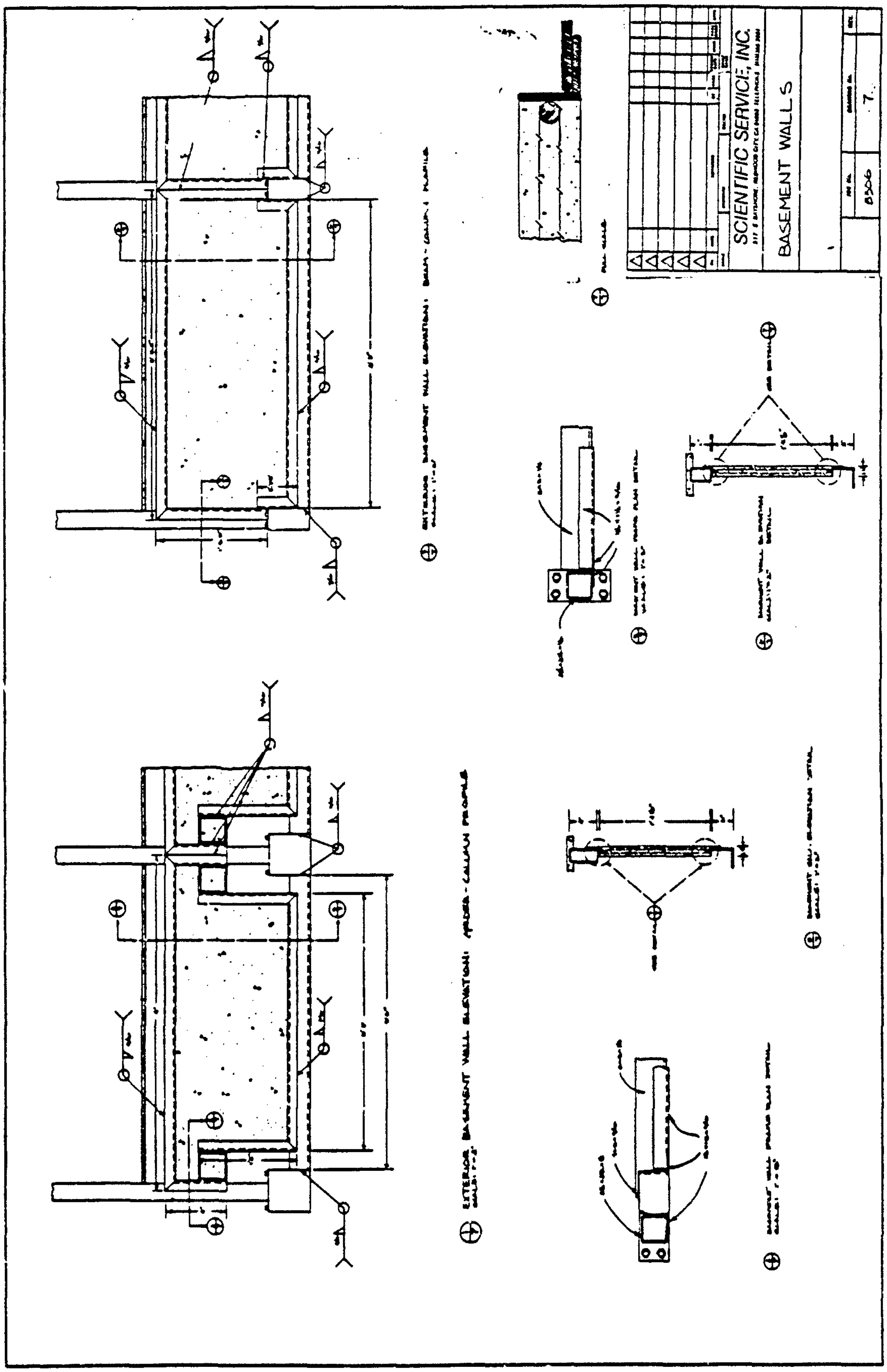
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BASEMENT WALLS
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APPENDIX 3

DEBRIS DATA FROM EXPERIMENTS 4140 AND 4145

Appendix B
DEBRIS DATA FROM HIGH RISE BUILDINGS
EXPERIMENTS 4140 AND 4145

Presented in this Appendix are the debris data from the steel frame and concrete frame one-fifth scale model buildings. The data are presented in tabular form using the following key:

Debris Type	Steel Building	Concrete Building
Column	SC	CC
Beam	SB	CB
Girder	SG	CG
Floor	SF	CF
Wall	SW	CW
Roof	SF*	CR
Window Frame	WF(S)	WF(C)

In most cases the above keys refer to pieces of the designated parts. Occasionally, a complete window frame or other part was recovered and these are so noted in the table. All of the window frames and wall panels were numbered, and in some cases it was possible to identify pieces of the debris. A drawing of the numbering scheme is presented in Figure B-1. The identifying numbers are presented in parenthesis in the table. The locations of the debris pieces were determined by laying out a radial line using measuring tape as shown in Figure B-2 and measuring the distance, either right or left, of that tape to the piece of debris.

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* It was not possible to differentiate between the steel building floor and roof fragments.

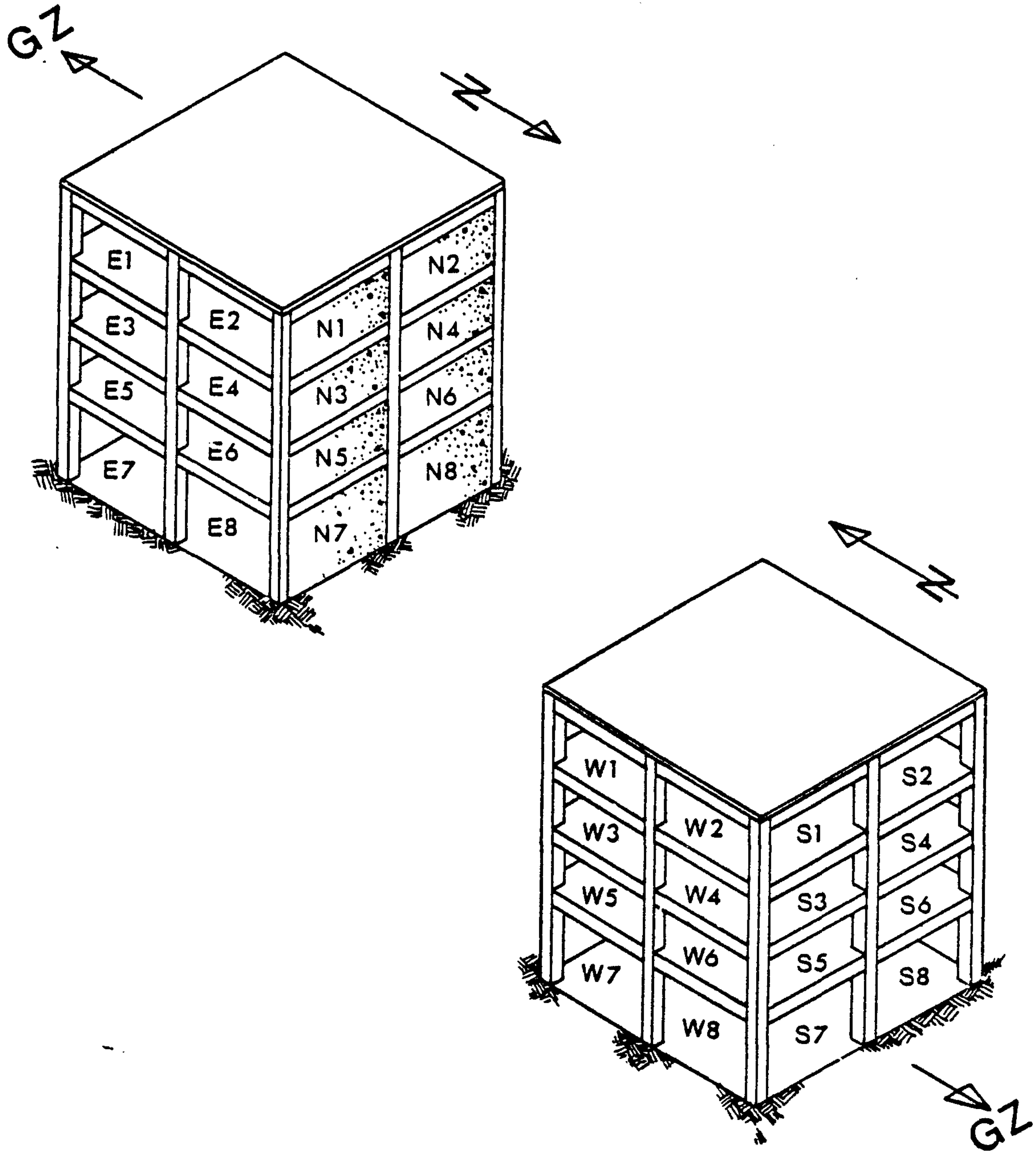

Fig. B-1. Numbering Scheme for Building Parts.

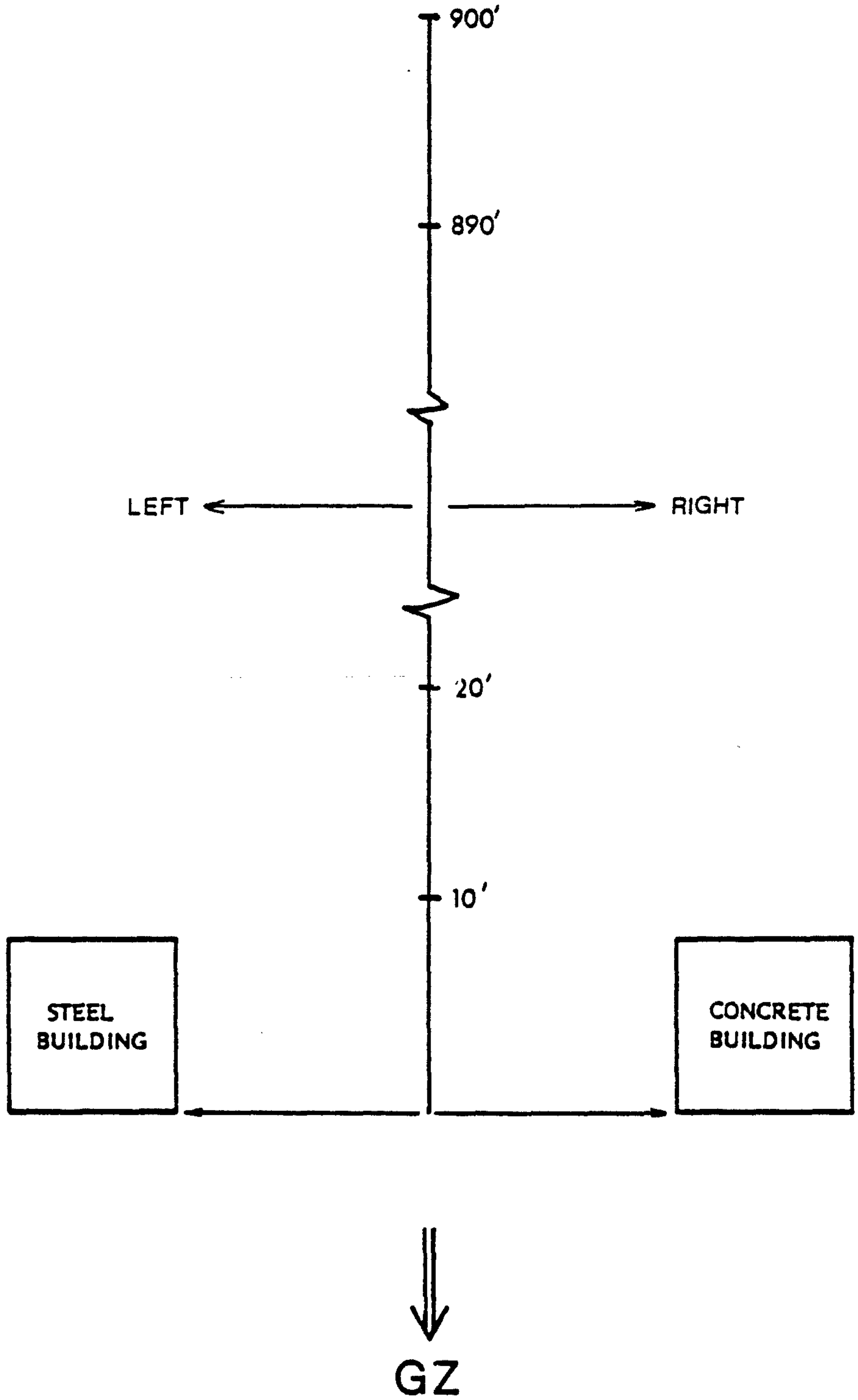

Figure B-2. Radial Line Layout for Debris Survey.
(Note: All measurements from front of buildings.)

Debris Location and Description

Distance Along Radial From Front of Bldg.	Distance From Radial	Description
16 ft	Left 18 ft	SF, SC, SB, SG, SW (see Figure B-3)
23 ft	Left 16 ft	SF
	Left 29 ft	SF
	Right 17 ft	Concrete Building (see Figure B-4)
32 ft	Left 12 ft	SB, SG (see Figure B-5)
	Left 18 ft	SF, WF
39 ft	Left 12 ft	SF, SB (see Figure B-6)
47 ft	Left 15 ft	SB, SG
53 ft	Left 13 ft	WF, SF (see Figure B-7)
55 ft	Left 22 ft	SF
57 ft	Left 26 ft	SF
63 ft	Left 13 ft	SF, WF
	Left 30 ft	SB
68 ft	0 ft	WF
	Left 14 ft	WF
	Left 25 ft	WF
71 ft	Left 21 ft	SF, SG
78 ft	Left 8 ft	SB
84 ft	Right 52 ft	CC
	Right 20 ft	WF
	Left 24 ft	SG, SB
	Left 44 ft	SB
	Left 52 ft	CG
	Left 18 ft	WF
	Left 15 ft	WF(S-S7)
88 ft	Left 9 ft	SF
	Left 8 ft	WF(S-S8)
	Left 15 ft	SF,WF
	Left 29 ft	SF

Distance Along Radial From Front of Bldg.	Distance From Radial	Description
94 ft	Left 50 ft	SB
100 ft	Right 22 ft	WF, WF
109 ft	Left 5 ft	WF(C-S3)
	Left 9 ft	WF
	Left 31 ft	WF
	Left 40 ft	WF
	Left 47 ft	WF, WF(C-N5)
	Left 57 ft	WF
121 ft	Right 37 ft	WF(C-W4)
125 ft	Right 27 ft	WF
	Left 13 ft	WF
	Left 41 ft	WF
	Left 56 ft	WF(C-S3)
128 ft	Right 32 ft	WF
	Right 8 ft	SB
134 ft	Right 35 ft	WF
138 ft	Right 6 ft	CG
140 ft	Left 5 ft	CG
143 ft	Left 7 ft	WF, WF
	Left 19 ft	WF, WF, WF(S-S5)
150 ft	Left 42 ft	SF, SB, WF
	Left 60 ft	WF
155 ft	Right 5 ft	CF
	Right 93 ft	WF(C-S5)
157 ft	Left 73 ft	WF(C-N8)
159 ft	Left 41 ft	SB
	Left 56 ft	WF(S-W1)
	Left 71 ft	WF(C-N4)
160 ft	Right 72 ft	WF
166 ft	Right 40 ft	CG
172 ft	Left 30 ft	WF
	Left 60 ft	WF(S-N7)

Distance Along Radial From Front of Bldg.	Distance From Radial	Description
179 ft	Right 41 ft	CG
	Right 95 ft	WF
	Right 88 ft	WF(C-S7)
	Right 19 ft	WF(C-W3)
182 ft	Left 81 ft	WF
	Left 89 ft	WF
183 ft	Left 60 ft	WF
	Left 35 ft	WF
184 ft	Right 25 ft	CF
	Right 10 ft	WF
188 ft	Left 87 ft	WF
	Left 6 ft	WF
	Right 7 ft	WF(C-W1)
190 ft	Left 65 ft	WF
	Right 39 ft	WF
193 ft	Left 36 ft	WF(C-S6)
	0 ft	WF
194 ft	Left 13 ft	WF(C-W6)
	Left 62 ft	WF
	Right 30 ft	CC
	Right 16 ft	CF
196 ft	Left 43 ft	WF
198 ft	Left 4 ft	WF
	Left 43 ft	WF(S-W3)
	Left 51 ft	WF
	Left 94 ft	WF
	Left 110 ft	WF
203 ft	Right 17 ft	CR
206 ft	Right 6 ft	CB, CG
207 ft	Left 31 ft	WF
208 ft	Right 17 ft	CG, WF(S-S4)
	Right 7 ft	WF

Distance Along Radial From Front of Bldg.	Distance From Radial	Description
215 ft	Right 6 ft	CC
218 ft	Left 8 ft	WF
	0 ft	WF(C-S5)
	Right 3 ft	CR, 7 ft X 4 ft (see Figure B-8)
222 ft	Left 67 ft	WF
	Left 45 ft	WF(S-W4)
	Left 12 ft	WF
	Left 5 ft	WF
226 ft	Left 57 ft	WF(S-N4)
	Left 21 ft	WF(C-N6)
	Left 21 ft	CR
	Right 56 ft	WF
231 ft	0 ft	WF
237 ft	Right 10 ft	SG, SB
	Right 38 ft	CF
260 ft	Right 47 ft	CB
266 ft	Right 20 ft	WF(C-S4)
275 ft	Right 7 ft	WF(C-N3)
	Right 37 ft	WF
281 ft	Right 67 ft	WF(C-S2)
300 ft	Right 68 ft	WF(C-S3), entire frame
	Right 84 ft	WF
	Left 63 ft	SB
	Left 30 ft	SW (S-8), CW (C-8)
304 ft	Right 11 ft	SW
308 ft	Right 276 ft	WF
309 ft	Right 59 ft	CW
312 ft	Right 10 ft	WF (C-N1)
317 ft	Right 2 ft	CW
319 ft	Left 16 ft	SW
327 ft	Left 23 ft	SW
	Right 27 ft	CW (C-7)

Distance Along Radial From Front of Bldg.	Distance From Radial	Description
329 ft	Left 1 ft	SW (5 small pieces)
342 ft	Left 7 ft	CF
343 ft	Right 22 ft	WF, WF
352 ft	Right 126 ft	CW (C-3)
362 ft	Right 173 ft	CC, WF
	Left 95 ft	SW
363 ft	Right 13 ft	SW
369 ft	Right 17 ft	SW
	Left 4 ft	SF (4 ft X 2¼ ft)
371 ft	Right 2 ft	CW
377 ft	Right 26 ft	CW
386 ft	Right 32 ft	CW (C-7)
	Left 157 ft	WF (SN-8)
400 ft	Left 95 ft	SB, CW (C8)
	Left 29 ft	SW, SW
413 ft	Left 32 ft	CW (C-6)
420 ft	Left 132 ft	SW
425 ft	Right 74 ft	CW
426 ft	Left 57 ft	SB
429 ft	Left 64 ft	SW, CW
	Right 1 ft	CW
448 ft	Left 115 ft	CB
449 ft	Right 1 ft	CB, CF
453 ft	Right 17 ft	SW
457 ft	Left 27 ft	CW (C-6)
460 ft	Left 33 ft	WF
	Left 62 ft	SB
	Left 117 ft	CB
470 ft	Left 17 ft	WF
481 ft	Left 23 ft	CW
	Left 48 ft	SW (S-6)

Distance Along Radial From Front of Bldg.	Distance From Radial	Description
481 ft	Left 11 ft	SW (S-7)
	Right 26 ft	SW
488 ft	Left 26 ft	SF
492 ft	Right 52 ft	CW
	Right 4 ft	CW
500 ft	Left 14 ft	SF
503 ft	Left 13 ft	SF, 10 in. X 20 in.
523 ft	Left 37 ft	SW (S-7), 10 in. X 20 in.
	Left 50 ft	SW (S-5), 14 in. X 18 in.
525 ft	Right 14 ft	SW (S-4)
541 ft	Right 21 ft	SW
543 ft	Left 140 ft	CW, 8 in. X 13 in.
548 ft	Left 48 ft	SW
549 ft	Right 14 ft	CW, SW
	Right 143 ft	CW (C-3), SW (S-7)
553 ft	Left 15 ft	SW (S-4)
562 ft	Left 11 ft	CW (C-2)
	Left 29 ft	SW (S-6)
571 ft	Left 138 ft	SW (S-7), 14 in. X 14 in.
583 ft	Left 71 ft	SF, 32 in. X 48 in. (see Figure B-9)
614 ft	Left 41 ft	CW (C-6)
628 ft	Left 128 ft	SF, 2 pieces, 24 in. X 24 in.
630 ft	Left 19 ft	CW, 6 in. X 6 in.
634 ft	Right 12 ft	SW (S-2), 12 in. X 10 in.
638 ft	Left 35 ft	SW, 10 in. X 15 in.
650 ft	Left 35 ft	SW, 12 in. X 10 in.
681 ft	Left 53 ft	SW, (S-1), 6 in. X 5 in.
687 ft	Left 41 ft	SW (S-1)
690 ft	Left 91 ft	CW, 6 in. X 18 in.
697 ft	Left 67 ft	SW, 6 in. X 10 in.
706 ft	Right 256 ft	CF, 32 in. X 48 in.

Distance Along Radial From Front of Bldg.	Distance From Radial	Description
707 ft	Right 156 ft	SF, 4 ft X 8 ft (see Figure B-10)
717 ft	Right 23 ft	CF, 6 in. X 6 in.
750 ft	Right 55 ft	CW (C-8), 4 in. X 10 in.
	Left 190 ft	CW, 6 in. X 10 in.
780 ft	Left 178 ft	CW, 6 in. X 8 in.
790 ft	Left 168 ft	SF, 16 in. X 32 in.
800 ft	Right 228 ft	SF, 16 in. X 24 in.
875 ft	Left 120 ft	SW (S-3), 8 in. X 8 in. (see Figure B-11)

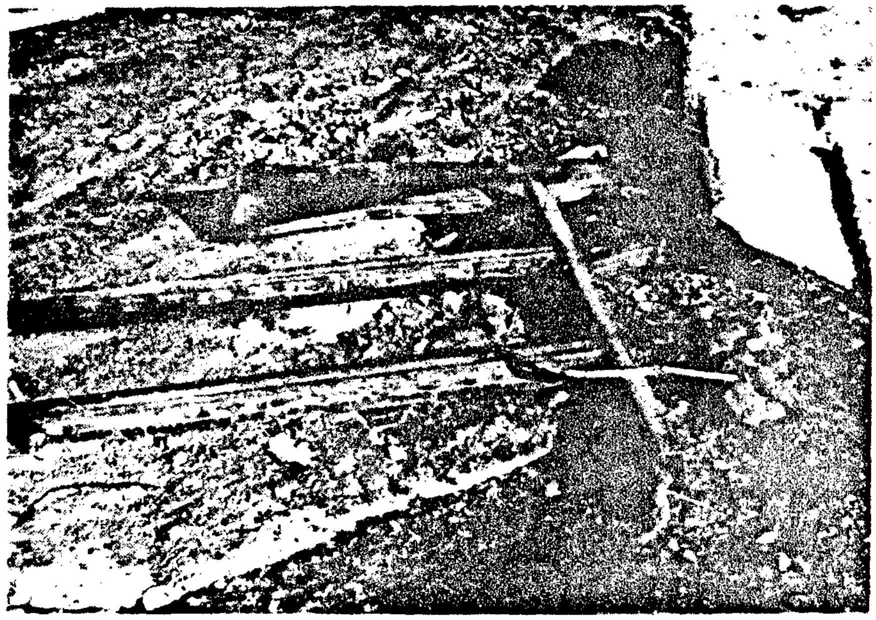

Fig. B-3. Debris From Steel Frame Building at 16 Feet.

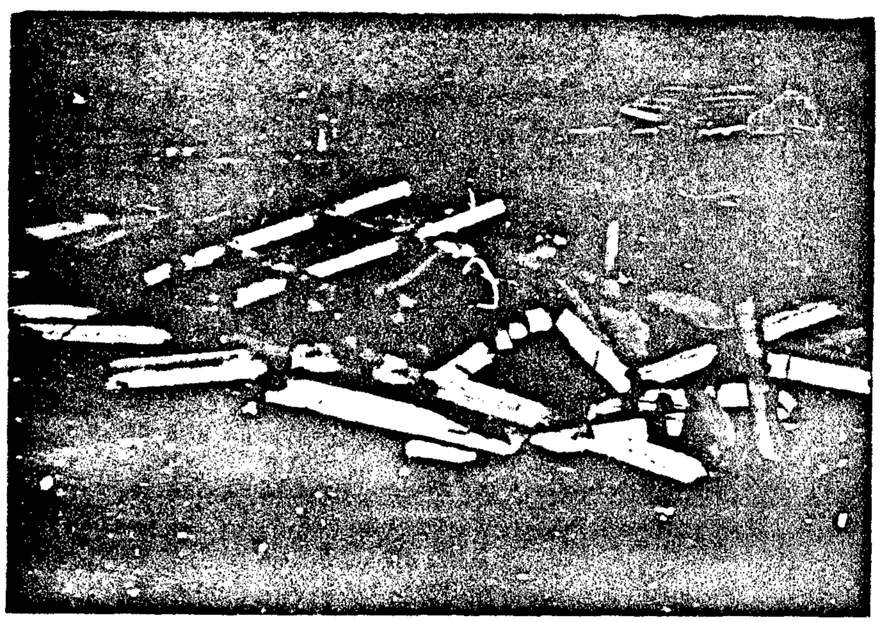

Fig. B-4. Concrete Building Debris.

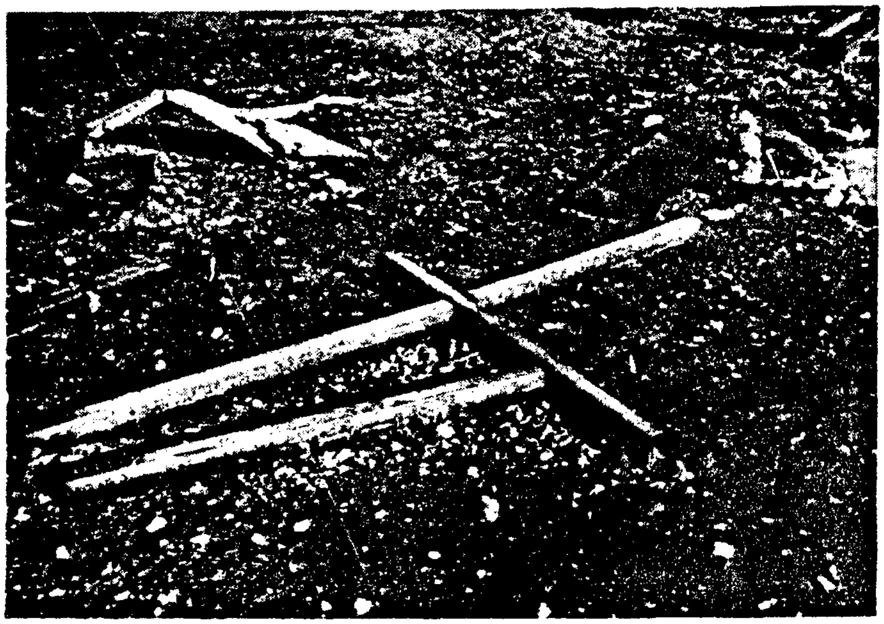

Fig. B-5. Steel Frame Debris at 32 Feet.

Fig. B-6. Steel Debris at 39 Feet.

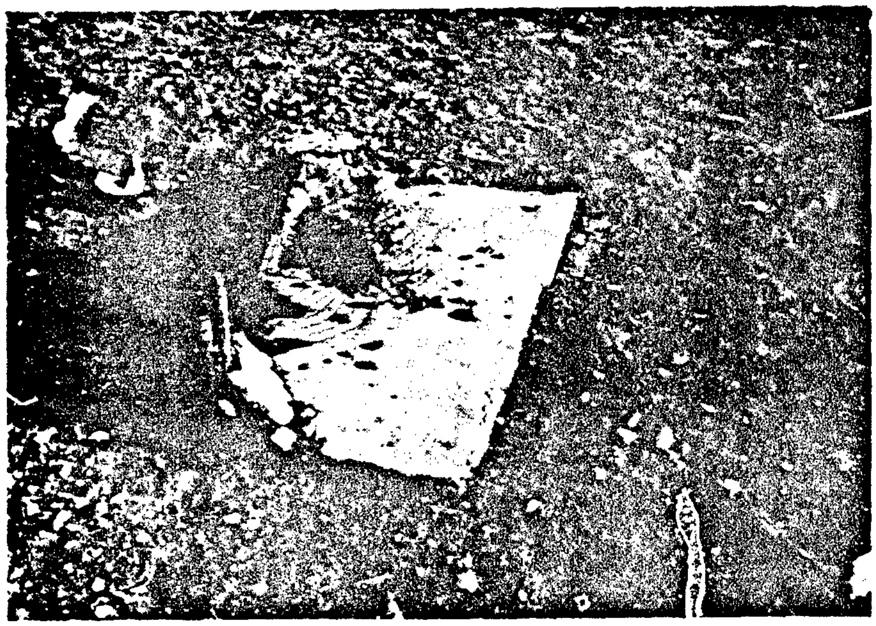

Fig. B-7. Debris at 53 Feet.

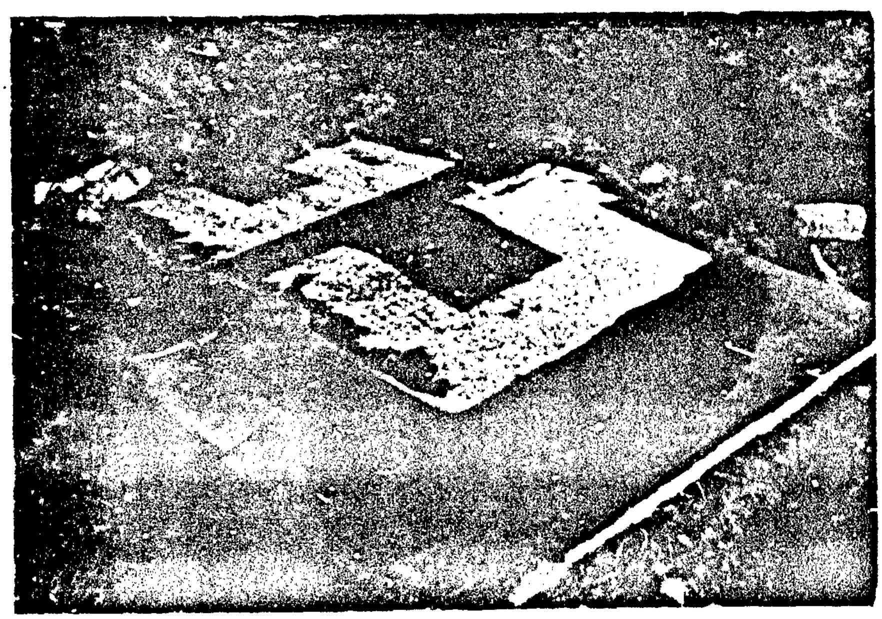

Fig. B-8. Concrete Roof Debris at 218 Feet.

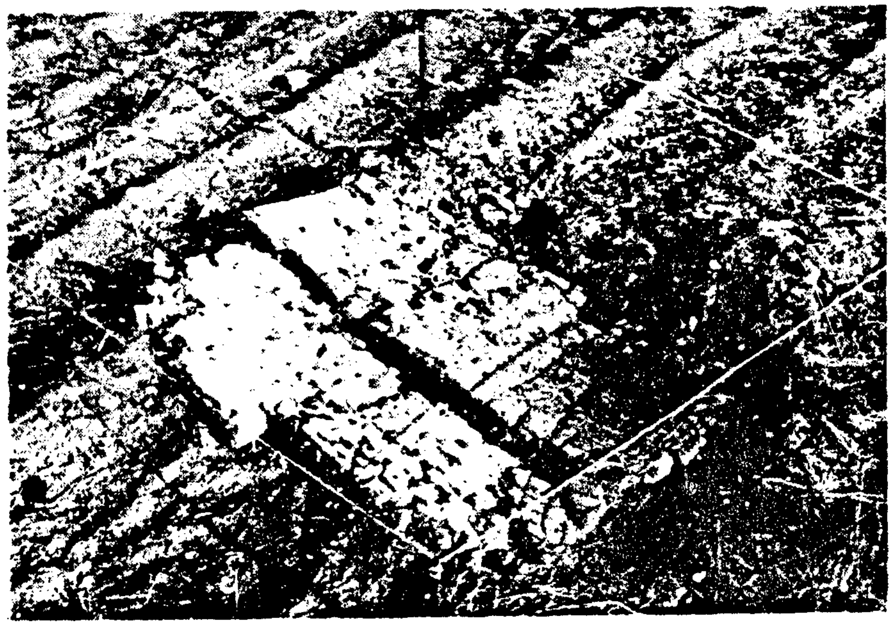

Fig. B-9. Steel Building Debris at 583 Feet.

Fig. B-10. Steel Building Debris at 706 Feet.

Fig. B-11. Steel Building Wall Fragment at 875 Feet.

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INDUSTRIAL HARDENING AND POPULATION BLAST SHELTER TESTS AT THE DIRECT COURSE EVENT Unclassified

March 1984

Scientific Service, Inc., Redwood City, CA
Contract EMW-C-1097, Work Unit 1121E 162 pages

This report presents the results of experiments conducted for the Federal Emergency Managment Agency at the DIRECT COURSE high explosive test on October 26, 1983 at White Sands Missile Range. The DNA-sponsored DIRECT COURSE event consisted of the detonation of 609 tons of ANFO at a height of burst of 166 ft. The experiments discussed in this report were conducted in support of Civil Defense planning and involved industrial protection and shelter design criteria. One group of experiments was designed to gather further experimental data on the concept of clustering as a method for hardening of industrial equipment. Two one-fifth scale model buildings were tested to obtain information on frame response, building collapse, and survivability of upgraded basements. Model basements walls and model shelters were also tested, and six types of expedient closures were fielded to test closure materials that could be easily installed by hand.

INDUSTRIAL HARDENING AND POPULATION BLAST SHELTER TESTS AT THE DIRECT COURSE EVENT Unclassified

March 1984

Scientific Service, Inc., Redwood City, CA
Contract EMW-C-1097, Work Unit 1121E 162 pages

This report presents the results of experiments conducted for the Federal Emergency Managment Agency at the DIRECT COURSE high explosive test on October 26, 1983 at White Sands Missile Range. The DNA-sponsored DIRECT COURSE event consisted of the detonation of 609 tons of ANFO at a height of burst of 166 ft. The experiments discussed in this report were conducted in support of Civil Defense planning and involved industrial protection and shelter design criteria. One group of experiments was designed to gather further experimental data on the concept of clustering as a method for hardening of industrial equipment. Two one-fifth scale model buildings were tested to obtain information on frame response, building collapse, and survivability of upgraded basements. Model basements walls and model shelters were also tested, and six types of expedient closures were fielded to test closure materials that could be easily installed by hand.

INDUSTRIAL HARDENING AND POPULATION BLAST SHELTER TESTS AT THE DIRECT COURSE EVENT Unclassified

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